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MECHANICAL ELEMENTS AND BEARINGS IN SPACE

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ABSTRACT 18484

Mechanisms operating in space are affected primarily by the low vacuum of the environment. In this study, three types of mechanical problems in space have been considered: (1) frictional characteristics under a high vacuum, (2) sealing of removable hatches, and (3) power transmission through a pressure barrier. The vacuum of space was simulated by a pressure in the order of 10^{-7} Torr.

It is concluded that friction is the consequence of molecular disorder in the interface between two mating surfaces. In space where conventional lubricants are inadequate, friction cannot be reduced to an acceptable minimum by ball, roller, or journal bearings. The problem must be attacked by methods of solid state physics which suggests the development of a special solid lubricant of extraordinary characteristics.

This special lubricant, considered to be an artificial crystal with a central cleavage plane of minimum shear strength, is the starting point for the development of a generally applicable space bearing which may provide the answer to problems of sealing and power transmission.

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PROPULSION AND MECHANICS BRANCH
PROPULSION AND VEHICLE ENGINEERING DIVISION

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MECHANICAL ELEMENTS AND BEARINGS IN SPACE

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SUMMARY

Mechanisms operating in space are affected primarily by the low vacuum of the environment. In this study, three types of mechanical problems in space have been considered: (1) frictional characteristics under a high vacuum, (2) sealing of removable hatches, and (3) power transmission through a pressure barrier. The vacuum of space was simulated by a pressure in the order of 10^{-7} Torr.

It is concluded that friction is the consequence of molecular disorder in the interface between two mating surfaces. In space where conventional lubricants are inadequate, friction cannot be reduced to an acceptable minimum by ball, roller, or journal bearings. The problem must be attacked by methods of solid state physics which suggests the development of a special solid lubricant of extraordinary characteristics.

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INTRODUCTION

During the last few years, malfunctions of instrumentations and mechanisms of orbiting satellites, and requirements for future space stations and manned space vehicles for long-duration, dependable operation in the vacuum of space have inspired a comprehensive study on the functioning of mechanical elements under such conditions.

Among such mechanical elements, bearings, torque-transmitters, and removable hatches have been selected for particular emphasis. The purpose of this report is to point out a line of reasoning and investigation which may lead to the solution of the problems.

Since the operational quality of bearings and other mechanical elements depends on the frictional conditions between the elementary parts, this study has been a concentration on the characteristics of friction under varying conditions - particularly under a high vacuum - in order to derive proper design principles for bearings intended to perform in space. In particular, the development and investigation of a torque transmitter capable of operating through a pressure barrier may be considered a practical combination of the friction and sealing problems studied.

Friction increases considerably in a high vacuum; in many cases, two sliding parts gall or cold-weld, particularly if the sliding surfaces are clean. The fact that the cleanliness of the rubbing surfaces is directly responsible for the friction effect, eliminated from the beginning any idea that friction in space is merely a matter of finding the right combinations of materials. Rather, the fact suggested an intensive study of the properties of solid surfaces to find out how to neutralize the free surface energies which are probably an important cause of the galling and cold-welding processes that occur in a high vacuum.

With this energy concept in mind, the testing of conventional bearings and links under a high vacuum by use of different materials combinations and lubricants could not be reasonable. It seemed logical to attack the problem by a basic study of friction under a high vacuum so as to develop an adequate theory on the mechanicsm of friction. In order to exclude all parameters connected with commercial bearings the frictional elements and geometry of the contact areas have been simplified.

This investigation has been partially sponsored by ARPA funding. Behavior of dry coated bearings under a high vacuum with respect to film thickness of the coatings was the objective of a contract with Columbia Broadcasting System (CBS), and the sealing of removable hatches was the objective of a contract with Consolidated Vacuum Corporation (CVC); the CVC contract is still effective. Results of these contracts are presented in Appendices A and B.

The work was helpfully supported by Mr. H. Bergeler, Chief of the Experimental Mechanics Section, Marshall Space Flight Center. The test program was coordinated and conducted by Mr. H. J. Nein whose valuable ideas contributed substantially to the accomplishment and evaluation of the tests. Mr. R. C. Edwards insured proper and accurate functioning of the test setups and vacuum systems.

SUMMARY OF THE PRESENT KNOWLEDGE ON FRICTION IN BEARINGS AND OTHER FLEXIBLE MECHANICAL ELEMENTS

Technical mechanisms are commonly a combination of solid kinematic elements which are in contact and which move relatively to each other. This combination of contact and relative motion results in a condition called friction. Friction is the fundamental condition necessary for the functioning of all mechanisms. In many cases, friction is required for effective transfer of energy; in many other cases such as functioning of bearings, links, etc., friction is an obstacle. In those cases in which friction is an obstacle, the effect on precise operation, reliability, and the lifetime of any mechanism is serious. In spite of the appreciation of the importance of friction in scientific applications, it is curious that no adequate theory of the fundamental nature of friction has yet been developed.

The simple law advanced by Amontons in 1699, that the friction force F is proportional to the normal load N

$$F = \mu \cdot N \tag{1}$$

is still a basic rule in mechanical engineering. The proportionality factor μ called the friction coefficient, is tabulated for most commercial materials combinations in engineering handbooks and is generally used as the basic design figure for mechanisms of all types, although its reproducibility is poor.

Since Amontons' time, many studies have been devoted to the nature of friction and its specific mechanism. The following facts about friction are now known:

1. Friction is independent of the area of the sliding surfaces and of the velocity of sliding.

2. There is a difference in friction between lubricated and unlubricated surfaces.

3. No surface is truly flat.

4. The most carefully finished surfaces have significant irregularities.

5. All surfaces are covered, more or less, with a layer of contaminants of varying thickness.

From this knowledge, earlier workers concluded that friction is the consequence of interlocking asperities.

With growing knowledge of the molecular structure of matter, attempts have been made (particularly supported by the extensive work of Sir William Hardy) to explain friction as the reaction of molecular forces at the interface of two sliding surfaces. An interesting study by Tomlinson interprets friction as being "the energy dissipated when the molecules were forced into each other's atomic fields, and were then separated."

Bowden and Tabor conclude from their comprehensive experiments that "under the intense pressure which acts at the summits of the surface irregularities, a localized adhesion and welding together of the metal surfaces occurs. When sliding takes place, work is required to shear these welded junctions and also to plough out the metal." This process, according to Bowden and Tabor, explains the friction phenomenon. These workers distinguished between the apparent area of contact (which they submit is of no influence) and the real area of contact A_r which results from the asperities supporting the load N of the sliding body. If p is the penetration hardness of the weaker material, then

$$N = A_r p \tag{2}$$

Where clean materials are in contact, the junctions usually cold-weld. Sliding of clean surfaces can take place only by shearing off the junctions where the shear strength of the junction can be considered equal to the bulk shear strength σ of the weaker material. Then, the tangential force F can be expressed by

$$F = A_r \sigma \tag{3}$$

Combining equations (2) and (3) and referring to equation (1)

$$\mu = \frac{F}{N} = \frac{\sigma}{p} \tag{4}$$

Since σ and p are similar properties of the weaker material, and since the load N, the surface roughness, the apparent area of contact and the velocity of sliding do not enter into equation (4), the coefficient of friction should be the same for a wide variety of materials under a wide variety of conditions. Indeed, this is confirmed by a wide range of testing; and this may also be the reason stated (Amontons) that friction is three-tenths of the applied load for all materials.

Equation (4) appears to be a very simple formula with which to calculate the friction coefficient from physical properties. Yet, because range is relatively wide in which the shear strength and the hardness vary within a quite small area of a sample, the resulting friction coefficient calculated with equation (4) is only a rough (and barely reproducible) approximation.

The fact that all solid surfaces under ambient conditions are covered by a layer of contaminants of varying thickness is not taken into account in equation (4). Such contaminants consisting of molecular or atomic particles precipitated from the surrounding air strongly adhere to the surface. They are generally unmoved even when heavy loads are applied to two surfaces in contact. This suggests that these contamination layers have lubricating qualities, i.e., they lower the friction, because the shear strength of such layers is obviously less than that of the bulk materials to which they adhere. Oils and greases belong in the category of "special surface contaminants." The earliest theories suggested that the viscosity of a lubricant is responsible for its lubricating qualities; however, this has been proved incorrect.

In the course of physico-chemical studies it was discovered that the long-chain molecules of oils are oriented quite regularly on a surface. One end of the chain adheres to the surface, while the chains themselves are packed vertically, erected like the hairs of a brush. The regularity of formation of the chain molecules, and likewise the sliding qualities (lowering friction), ameliorate with increasing adsorption between surface and oil molecules and with smoothness of surface. In this state, the oil may be thought of as a flexible crystal.

This phenomenon indicates a direct correlation of the friction effect with the properties of very thin atomic or molecular layers. The stability of such friction-reducing layers, on the other hand, certainly depends on the environmental conditions, particularly on the atmospheric pressure (apart from the composition of the atmosphere involved). It is a known fact that any state of matter is a consequence of partial pressures. If the ambient pressure drops low enough, any kind of material tends to evaporate. Of course, this occurs also to layers on solid surfaces; consequently, friction increases, particularly in the vacuum of space. A better grasp of this situation can be obtained by testing the influence of the surface texture on friction in a simulated space environment.

THE SIMULATION OF SPACE

Characteristics of the ultra-high vacuum of space are not only the very low pressure of the environmental atmosphere but also the mean free path of gas particles. The mean free path (the mean distance of a free-moving molecule without collision with another one) increases tremendously with decreasing density. Even in a vacuum of the order of only 10^{-6} Torr, the mean free path of the air molecules is of the order of 10^2 meters. To simulate such a vacuum a spherical vacuum chamber with a radius of at least 10^2 meters $\approx 3.10^2$ feet is required. In smaller chambers the molecules frequently hit the chamber wall during one free path--rebounding across the same space repeatedly, so that a false pressure level is recorded. Clearly, commercial vacuum systems, even with pumps of extremely high capacity, are quite inadequate.

With the problem of molecule rebound in mind, it seems impossible to remove contamination layers from solid surfaces in a technically producible vacuum: many molecules would bounce back from the chamber wall to their original locations; therefore, these vacua do not actually simulate space. But, by increasing the thermal energy of the layer molecules, combined with the evacuating energy of the pumping system and with cooling the chamber wall can provide approximation to space conditions, at least on the surfaces to be tested. This was the method of investigation reported herein.

The vacuum system consisted of a cylindrical vacuum chamber 6 feet in length and 4 feet in diameter, pumped out by a large diffusion pump having a 32-inch flange. Pressure reduction achieved was in the order of 10^{-7} Torr (FIG 1). Recently, a smaller vacuum system equipped with an overdimensioned diffusion pump and an ionization pump has been operated to provide better testing flexibility.

THE TEST PRINCIPLES

The science of mechanical engineering distinguishes between static friction and kinetic friction. Static friction (before sliding or rolling starts) is generally observed to be greater than kinetic friction (during the sliding or rolling). Tests have shown, however, that the static coefficient of friction is a function of the time the surfaces have been in stationary contact. Within a time interval of contact of $\leq 10^{-3}$ sec, the kinetic coefficient proved equal to the static coefficient of friction. It must be, then, that the particles at the interface of two sliding bodies need time to reorient and to accommodate to the different situations of stationary or sliding contact in order to balance the interacting forces.

The sliding process was studied in terms of three types of surface contact: flat surface, three-point, or one-point.

The simplest way to determine the friction coefficient between two different materials is by using an inclined plane (FIG 2). In this case the friction coefficient equals the tangent of the inclination angle:

$$\mu = \frac{F}{N} = \tan \phi$$

This method, of course, gives no details on the sliding process at the interfaces.

Details on the sliding process were obtained by pulling a tripod sample (three-point contact) over a flat plane by means of a slow-geared driving mechanism (FIG 3). In this case, the friction forces exerted to a force transducer installed in the pulling shaft were recorded. The friction coefficient, likewise, can be derived by means of equation (5).

For the one-point contact, two cylindrical samples touching crosswise were rubbed against each other by an oscillating mechanism (FIG 4). One sample was oscillated while the other sample was loaded with variable loads from zero upwards. The load sample in this system acts as a damping element. The recorded vibration is delineated as a linearly damped sinusoidal curve (Coulomb or friction damping). The decrement for each quarter of one cycle is directly proportional to the friction coefficient according to the equation

$$\mu = \frac{F}{N} = \frac{bk}{N} \tag{6}$$

where b = the decrement for 1/4 cycle and $k = 0.984 =$ g/cm the spring constant of the particular system utilized. Equation (6) is easily derived from the equation of motion of the system which is

$$m\ddot{x} = F - kx \tag{7}$$

or

$$\frac{m\ddot{x}}{k} + x = \frac{F}{k} = b \tag{8}$$

where b, obviously, represents the static elongation of the spring produced by the friction force F. From equation (8) it follows

$$F = bk$$

and consequently, equation (6).

The test set-ups representing the principles discussed were modified frequently during the test period for obtaining specific information of the friction process.

TEST SAMPLES AND MATERIAL SELECTION

The friction problem of space mechanisms, as indicated above, is believed to be a surface problem rather than a problem of compatible materials combination. On the other hand, it is well known that material hardness and electrical properties largely dictate the surface properties. For this reason, three types of materials were investigated in this study: (1) hard metals, (2) soft metals, and (3) non-metals. These materials are listed in Table 1.

For the inclined plane and tripod testing, the samples are represented by a base plate and a rider. The disc-like base plates were made with diameters of 4-in (10 cm) and 0.5-in (1.25 cm) thickness. The riders for the inclined plane were cylindrical bodies with different diameters for varying the apparent area in contact. For the tripod, the riders consisted of a small metal disc on which 3 cylindrical samples of like materials were mounted, the free end of the samples rounded hemispherically. The samples for the oscillating disc are small cylinders of 1.25 in $\approx$ 3.2 cm in length and 0.67 in = 0.425 cm diameter.

The surface roughness of the samples is an important parameter. Guideline for the surface roughness was the Military Standard 10A. To reduce interlocking of asperities, most of the samples were prepared with a surface finish of 2 to 5 micro-inches.

In order to remove the contamination layers, the samples were chemically cleaned and heated in vacuum, gradually, up to 360° C (in some cases up to 600°C) at the tripod tester, and to 150°C at the oscillating disc tester.

TEST PROCEDURES AND RESULTS

With the three testing methods discussed above, various materials combinations have been tested under varying conditions. The number of tests accomplished within each category is indicated in Table 1.

The tests show the striking fact that the friction coefficient varies considerably with environmental conditions: for some combinations more; for others less. In FIG 5 the maximum and minimum friction coefficients, achieved under varying external conditions (pressure, temperature), are delineated for all material combinations tested. The minima are pretty close to the same magnitude in all cases while the maxima vary on a rather large scale. Surprisingly, a friction coefficient between 0.2 and 0.3 is possible for all materials under normal conditions. This reinforces Amontons' general statement that the friction coefficient of all materials is 0.3. On the other hand, this result shows the unreliability of the friction coefficient. It also demonstrates the poor reproducibility of the friction coefficient. These findings, however, do not indicate the reason for the variability of the friction coefficient. One conclusion, seemingly justified by the previous result, is that the different properties of bulk materials of the rubbing samples are of minor importance to the frictional effect. The friction phenomenon appears to be the statistical result of the momentary condition of a very small area or the texture of two surfaces in contact.

This conjecture is well supported by test results in three-point or one-point contact. With test setup No. 2 (tripod rider) and setup No. 3 (oscillating disc), the record of the friction forces reveals a dramatic story of a series of events which obviously occur at the rubbing surfaces. The average course of the curve (indicating the friction forces during a period of several hours where the external pressure was changed from atmospheric pressure to a vacuum in the order of 10^{-7} Torr and the temperature increased and decreased again) shows characteristic effects typical for almost all materials combinations. From atmospheric pressure to high vacuum, the friction coefficient decreases. After a certain time, it increases again to a multiple of the value measured at atmospheric pressure.

This increase of the friction coefficient in high vacuum is accelerated by heating the samples. Here it should be understood that maximum friction does not always occur at maximum temperature. On the contrary, with decreasing temperature, the friction increases, until with further decreasing temperature the friction decreases very slowly. Even if the atmospheric pressure and temperature are restored, the friction returns to the original value. FIG 6 through 10 represent typical examples of such a hysteresis process. The combination of elevated temperature with a vacuum of 10^{-7} Torr may be considered an equivalent to a much higher vacuum without temperature increase, as will be explained in the following section. The process discussed above is fairly reproducible.

There are, however, some exceptions to the general rule considered above. Tests with sapphire in combination with certain metals showed a continuous decrease of friction under a high vacuum, even at elevated temperatures (FIG 11 and 12). In combination with other metals, particularly with Hastelloy (FIG 13), the friction of sapphire increased in vacuum as generally observed. In FIG 14 through 23 the spreading of the friction coefficient during several tests has been plotted for various materials combinations versus vacuum at constant room temperature. Most combinations show the trend of increasing friction in high vacuum while FIG 20 through 23 clearly demonstrate decreasing friction with increasing vacuum.

A similar effect has been observed with an experiment inspired by the so-called stick-slip process (FIG 24) occurring during maximum friction periods under a high vacuum. This stick-slip process is characterized by an increase of friction followed by a sudden breakdown. To equalize such heavy "friction-oscillations," commercial powdered magnesium-carbonate was rubbed roughly onto the surfaces in contact, and the adverse stick-slip behavior was substantially eliminated. FIG 25 through 27 show the effect of $MgCO_3$ in comparison with the behavior of the unprotected surfaces of some materials combinations. $MgCO_3$ decomposes under a high vacuum to MgO and CO_2, the magnesium-oxyd forming very tiny uncontaminated crystallites which are the obvious lubricating agents evidenced in FIG 25 and 26. However, FIG 27 shows the dependence of the lubricating qualities on the particular characteristics of the substrate surfaces. Here, the same "lubricant" ($MgCO_3$) behaves adversely.

The discrepancy in the behavior of different materials combinations under a high vacuum has been confirmed by another test series in which the pressure was changed repeatedly from atmospheric pressure to high vacuum during a long test run. In this case again, with some materials combinations, the friction in vacuum was lower than at atmospheric conditions; while with other combinations the results were the reverse of what can usually be expected (FIG 28 and 29).

The results reported above showed up again, in a modified manner, with the one-point contact tester (oscillating mechanism). In this test series, the load of the rider sample was changed from 0.25 to 2.5 grams. FIG 30 shows the linear increase of the friction with the load for a selection of materials combinations tested under atmospheric conditions. The same selection is shown in FIG 31; however, it was tested under the high vacuum. The comparison of the two figures indicates that the sequence of the materials combinations, with regard to their friction coefficients, was in some cases changed considerably. This proves that an increase of friction under a high vacuum cannot be considered a general rule.

DISCUSSION OF THE TEST RESULTS AND CONCLUSIONS

The test results reported in the previous section indicate that the friction effect between two sliding mechanical elements originates in the very narrow region at the interface between two surfaces. The bulk material of the sliding element, obviously, is quite unimportant in the process. This follows from the fact that friction can change considerably while the bulk of the materials does not change.

On the other hand, it is well-known that any fresh surface is immediately covered by a layer of foreign particles, generally oxygen and water vapor, from the surrounding atmosphere. These surface-contaminating adsorption layers have a usual thickness of 5,000 to 10,000 Angstrom units (which is in the order of hundredths of a micro-inch).

The adsorbed particles clearly act as lubricant. The lubricating properties change with the thickness of the adsorbed layer, which is a function of the surrounding pressure. Since the bonding energy of the adsorbed particles to the substrate surface is certainly much weaker than the bonding energy of the substrate particles among each other (that is, since the adsorbed particles are more volatile than the substrate particles) the contamination layer will gradually evaporate with lowering of the environmental pressure. This evaporation process will be advanced either by the vacuum of space (10^{-11} to 10^{-14} Torr) or by a combination of a relatively low vacuum (test vacuum 10^{-7} Torr) with heating of the samples to a certain temperature. By means of the heat, the evaporation rate of the adsorbed gases is raised to a degree which corresponds with the evaporation rate at normal temperature in a much higher vacuum; thus, the test procedure indicated in the previous section may be considered a simulation of a vacuum higher than 10^{-7} Torr.

With decreasing thickness of the contamination layers the substrate surfaces draw closer to each other so that their inherent free surface energies become increasingly effective. The lubrication properties of the contamination layer are reduced and the friction coefficient increases. If the layer is completely evaporated, the clean sample surfaces join each other in atomic distances. In this stage, both surfaces form joint lattices--this means they weld together--a process known as "cold-welding". Even super-finished surfaces are not really flat; they have summits of the order of 500 Angstroms. So, the cold-welding process does not encompass a situation of the total surfaces sliding over each other, but only the summits which are in intimate contact momentarily. This situation exists prior to the complete evaporation of the contamination layer where the summits of the surfaces exceed the thickness of layer fragments. This is the period of the so-called stick-slip process which is illustrated by the saw-tooth pattern of the recorded friction forces during testing (FIG 24).

The hysteresis of the friction forces observed during the test runs is the consequence of the reduced sample temperature. In a vacuum of 10^{-7} Torr there are still enough gas molecules present in the "space" blanket which lubricate the sample surfaces again if the temperature is low enough. The "recontamination" takes a certain time, thereby delaying the "recovery" and causing the hysteresis condition. In outer space, this recovery process is most unlikely to occur because of lack of sufficient surrounding particles.

The decrease of friction generally observed during the first period of operation under high vacuum, leads to the conclusion that the thickness of the contamination layer built up under atmospheric conditions does not provide optimum lubrication qualities of the layer. After a certain outgassing as a result of high vacuum, the optimum thickness develops automatically and lowers the friction. If the thickness decreases more, the friction increases again, rapidly exceeding the original magnitude. The difference of this effect from material to material with regard to intensity as well as duration, points to a strong correlation between the properties of the substrate surface and the properties of the coating material. This effect, already observed by other workers, seemed to be important enough to make it the subject of a separate study. This was done by the contract with CBS Laboratories. During that study ball bearings were coated with silver (Ag) of varying thickness and were run at different speeds up to 60 hours under a vacuum of about 10^{-8} Torr. The results were compared with similar studies by Bowden and Taber on Indium (In) coated specimens. In both cases, results strongly supported the concept of an optimum film thickness. Another remarkable result of the CBS study is confirmation that the friction-reducing efficiency of the optimum film thickness decreases with duration of stress--even with optimum thickness of the coating, the friction of bearings increases the longer the bearings are operated under a high vacuum.

So far, the consideration of friction under a high vacuum might lead to the conclusion that the friction phenomenon is attributable only to the quantity of surface contaminations or deliberately applied coatings. The test results presented in the previous section, and likewise some occurences in the CBS study, strongly indicate that in some cases surfaces behave in an unexpected and inexplicable way which makes it unlikely that contamination is the sole cause of the friction. If quantity were the determining factor, it could be expected that the characteristics of friction during similar test conditions would be the same for different materials since the contamination layers are built by the same atmospheric compounds and even the thickness of the layers could be expected to be the same on different materials if the thickness were a function of exposure time. Rather, the variation of the test results from one material to the other as presented in FIG 6 through 13 indicates that neither the frictional properties of the contamination layers nor their thicknesses can be similar on different materials. The change in friction sequence of a series of materials combinations under different environmental conditions shown in FIG 30 and 31, disproves the idea of contamination layers as the only source of difference. This fact is made more pronounced by the tests with repeated pressure change from atmospheric pressure to high vacuum (FIG 28 and 29). There the different effect of the surface layer on different materials is obvious. Although these figures show the effect of high vacuum in the initial phase without heating of the samples, they indicate (1) that the adsorption forces for similar layers at different surfaces are different, (2) that the thickness of the layers at different surfaces is different; this follows from conclusion (1), and (3) that the optimum thickness for low friction is different at different surfaces. The tests with magnesium-carbonate also demonstrate a different effect of the layers of the same quality at different surfaces (FIG 25 through 27).

These conclusions point necessarily to a substantial influence of the momentary nature of the substrate surfaces. It seems that there is a pronounced interaction between the substrate surface and the contamination layer. In order to understand this mechanism, it must be viewed in terms of the atomistic structure of matter.

At the atomic level the term "surface" is hard to define. The substrate as well as the contamination layer is an agglomeration of particles, superficially distinguished only by the types of particles and their densities. Each particle is a complex system in itself: the nuclei represent the mass concentration, the far-distant electrons compensating the forces due to mass concentration. While the nuclei in a solid are oscillating thermally around a defined location, the electron configuration may be considered a very flexible and relatively easily destructible network. If two atoms approach each other the shape of their electron network deforms and in many cases the outer electrons interlock with each other. Such, only gradually different, occurrences are implied in suchphysical terms as "chemical bond", "van der Waals forces," "polarization," "adsorption," etc. Fundamentally, all these terms indicate consequences of the very same mechanism.

From the atomistic point of view, a system of accumulated atoms is most stable in the crystal stage (atoms arranged regularly). In the interior of the crystal the free forces of each atom are balanced in all directions. The core is supported by a regular field of forces due to the regular electron configuration surrounding it like a ball suspended three-dimensionally by springs. At the surface, however, this spring system, i.e., electron configuration, is disturbed and a certain portion of the structural energy is free.causing surface tension. The regularity of the crystal structure makes possible the field of free surface energy of corresponding regularity.

Metals and many other solids are usually a conglomerate of many disoriented tiny crystals. Thus, a freshly cut metallic surface resembles a mosaic of many different crystal faces which, due to the anisotropy of physical properties in a crystal, produce a very irregular field of free surface energies and which also are responsible for the inevitable irregularity of the surface flatness. The consequence of the irregularity of the surface energy field is the irregular density of particles adsorbed from the surrounding atmosphere. Due to this fact in conjunction with the irregularity of surface flatness, the interface between two solid surfaces appears, considered under the molecular scale, as a chaotic agglomeration of particles of different energy. The disorder of these particles is of such a degree that the actual surfaces can no longer be distinguished.

This concept of atomic disorder is more complete if the particles themselves are visualized as systems of an atomic nucleus surrounded by scores of electrons. These electrons form a network of variable strength between the nuclei, and friction between two sliding microscopic surfaces actually is nothing but the disruption of this electron network. Due to the inhomogeneity of the electron network, fairly uniform chunks of particles are torn off. This effect is called "wear." From this point of view, explanations of friction – such as being the consequence of interlocking asperities, or of the shear strength of the weaker substrate material, or of the surface tension between the materials in contact-are after all, only different aspects of the same fundamental mechanism, the consistence and elasticity of the electron network in interaction with the incorporated atomic nuclei.

The correlation of friction and electrical charges (separation of electrons) is well known from the ancient experiment of rubbing a glass rod with a calfskin. In this experiment, the contact of two different materials is the essential procedure, while the friction is a particular type of separation. At contact, the mating layers of particles tend to form an electrical equilibrium. This process requires a measurable time. Some particles shift to other locations (migration) due to the inhomogeneity of the surface energy field. At separation, whether normal to the original planes or parallel (sliding friction), the equilibrium in the interface is disturbed and friction may be considered the integral of all forces required to break up the scores of individual equilibria involved. Because of natural surface irregularities discussed above, the friction forces will usually be much larger than the forces necessary to separate normally to the original planes, since sliding results in a forced movement of a tremendous number of particles which are at a certain energy level. In connection with this, note that at normal separation the real contact areas are very small and the disturbing effect on the interface network is marginal. If, however, the surfaces in contact are extremely flat making the true contact area large, then even the separation normal to the planes requires relatively large forces, as observed in the mutual adherence of J-blocks. Reduced friction by rolling may be explained by the fact that in this case the real area of contact is extremely small and the separation at any instant is divided into two components, one normal to the momentary planes, and a very small one parallel to the planes, so that no substantial interfacial movement of particles is generated.

This simplified concept of the atomic interfacial mechanism of two solid surfaces reveals the close relationship between friction and the vacuum sealing problem. It also points convincingly to the inhomogeneity or disorder of the interface as the ultimate source of the friction problem as well as the sealing problem. The irregularity starts with the natural mosaic texture of metal surfaces. The multitude of different crystal faces on a metal surface bared by the machining process, provide a bundle of free surface energies of different but sharply defined and directed intensity due to the anisotropic characteristic of crystals. As the consequence, the contaminating surface layers will accumulate over the surface with the result of a pronounced disorder of particles at the surface (which, it must be noted, do provide a certain strength against deformation). This adverse situation is intensified by the irregularity of the contour (flatness) of the surface.

The advantage of proper orientation of particles in the interface has already been proved by the application of certain long-chain oil molecules which, as discussed in a previous section, arrange themselves like the hairs of a brush on the surfaces in contact. With the solids molybdenum-disulfide and graphite, the particularity of the crystal structure provides the same kind of natural orientation. Both materials build stratified lattices with very tight packaging of particles in particular planes, while normal to these planes the distance between the particles is large and the cohesive forces are weak. This provides for easy cleavage of the lamellae of the lattice which occurrence reduces friction when those substances are used as a lubricant between two rubbing surfaces. The desirable lubricating properties of graphite are supported by water molecules located between the stratified graphite lamellae – for this reason, graphite cannot be used as a solid lubricant in a high vacuum. Under these conditions the water outgasses and the graphite lamellae stick together.

DESIGN CRITERIA FOR BEARINGS OR OTHER MECHANICAL ELEMENTS OPERATING IN SPACE

The test results of this study are in many respects identical to the findings of other workers. The most significant one is that friction generally increases under a high vacuum. This phenomenon is a very serious problem in the design of space-operating mechanisms. Outgassing and decomposing make liquid lubricants impracticable for use in space - and there are few usable solid lubricants. This situation is not encouraging.

Interpretation of the test results, however, yields conclusions which provide proper design criteria for sliding contact areas of all mechanisms intended for space operation. Because friction is a consequence of surface irregularities and interfacial disorder, and because friction decreases or increases depending on the type, thickness and structural nature of surface layers, the proper approach must be one of improvement of the base surfaces in sliding contact, and on proper atomic orientation of the interfacial particles.

As pointed out earlier, highly finished surfaces are not really smooth. On the atomic level, irregularities of superfinished surfaces have startling "mountain peaks" ranging from 500 to 1000 times the atomic distance. This has been attributed to the relatively coarse mosaic texture of the surface crystal grains. Reduction of the grain size of the surface crystals to a very minimum will facilitate equalization of the asperities during the surface finishing process. This suggestion seems to be in conflict with the earlier concept of eliminating atomic or molecular disorder at the surface; yet the extreme refinement of the surface grains to the size of the elementary crystal unit or of the single molecule would create a state of ideal disorder (which is synonymous with ultimate homogeneity). But, with regard to the discontinuity characteristics of matter, such a condition (ideal disorder) can be considered equivalent to a state of the highest order. The relatively low friction on glass with its amorphous structure (high degree of disorder), the reduced friction on fine grain ceramics (pyroceram), and the friction decrease on Beilby layers, may be considered an experimental proof of the theory of boundary layers of high order. In this respect, the recently reported achievements in producing amorphous metal layers may be promising prospects for development of space bearings.

Judging from the experiments conducted during this study, it appears that the specific preparation of the base surfaces in the way discussed above, is not the only prerequisite for the proper functioning of mechanisms under space conditions. The tests have shown that surface layers of different types of materials and different thicknesses can alter the frictional characteristics. The different frictional behavior of different layers is the consequence of the specific interaction between the mass particle and electron distribution within the layer, and the resulting energy field of the particle distribution of the base surface. In some cases, the characteristics of the layer are such that the base surface field is screened and thus weakened; in other cases, the effect is just the reverse (FIG 25 through 27). This process will be most effective and clearly defined at a certain thickness of the molecular layer, depending on the maximum probability of regular particle orientation. This condition was designated the optimum film thickness in the previous discussion. The resulting surface energy field may be weakened further by addition of more molecular layers of other materials. By proper stratification of a multitude of molecular layers it should be possible to combine two similarly prepared surfaces with a central area of contact having phobic characteristics. Under ideal conditons, the shear strength in the plane of the contact area would be zero and friction would be eliminated! On this scale, the stratified film between the two base surfaces would actually be an artificial crystal with cleavage planes of shear strength decreasing to a minimum from one surface and then again increasing shear strength to the other surface. Such a film applied to a shaft and sleeve of a journal bearing could be compared with an aggregate of concentric thin cylinders with, first, increasing and then again decreasing mutual clearance. The "clearance" between the molecular layers (cylinders) is provided by the relationship of electron configurations between the different layers--by the naturally created interatomic balance between attractive and repulsive forces in a way similar to that of a natural crystal. In this pattern, the lubricating qualities of such a stratified film are the consequence of the electron clouds between the molecular layers (electron lubrication) which provide the stability of distance between the layers, and the consequence of the absolute vacuum between the atomic particles, nuclei and electrons (vacuum lubrication). From this point of view, the vacuum is the ideal "lubricant," if properly utilized. This fact is demonstrated by nature herself with her infinite variety of frictionless atomic and celestial mechanisms. The presently widespread opinion that vacuum is the main obstacle for space-operating mechanisms is actually a physical contradiction, already disproved by many orbiting satellites. Where there is no matter, there is no resistance and, consequently, no friction. Within atmosphere, orbiting of a satellite without continuing power would not be possible. As far as friction in bearings is concerned, not the vacuum but the lack of techniques to use the vacuum properly, is the principal problem of today.

The stratified film lubrication concept makes the distinction between sliding friction and rolling friction meaningless. This distinction should be recognized for what it is: a consequence of the prevailing failure to comprehend the mechanism of friction. If a properly stratified shell lubricant of the kind suggested above can be found or synthesized, there will be no need to complicate space vehicle mechanisms by sophisticated designs such as ball, roller, or needle bearings. It seems that the optimum approach can not be realized in the ball bearing concept.

Introduction of a workable, stratified shell lubricant will automatically solve two other important problems of space-operating mechanisms: sealing and power transfer through a pressure barrier. Proper sealing depends largely on the extension of the area of intimate contact between two surfaces to be sealed. The area of actual intimate contact is small compared to the total sealing area because of the surface irregularities discussed above. So areas with larger surface-to-surface distance are sources of continuous leakage, and tests conducted so far have shown that in spite of application of extreme pressure, the leakage cannot be eliminated by any means presently known. But even if the area of intimate contact could be made optimum, the sealing surfaces would weld together and could not be separated without destruction. With a stratified shell lubricant – or stratified shell seal as it is better called for this purpose – the intimate contact is warranted, and the cold-welding is eliminated due to the phobic characteristics of the cleavage planes. The applicability of the stratified shell seal for power transmission is based on the fact that this problem is both a lubrication and a sealing problem.

The experimental approach to the stratified shell was not possible during this study. The basic ideas, however, such as the importance of the lamellar characteristics, and the regularity and optimum thickness of molecular layers for reducing friction in bearings, were discussed in detail with CBS representatives in connection with the CBS contract. These ideas are being explored further by CBS under otherwise funded contracts.

Summarizing, the test results of this study lead to the conclusion that friction between two mating surfaces is the consequence of atomic and molecular disorder within a margin of several thousand Angstrom units normal to the surfaces in contact. This understanding suggests the need for an artificial solid lubricant of special molecular structure. If formed into a cylindrical cartridge such a lubricant could be placed between the shaft and sleeve of a journal bearing. The lubricant is conceived as a composite of a series of well-oriented molecular layers of different materials between two mating solid surfaces. The facing substrate surfaces are each covered with an amorphous layer of a specific thickness in order to homogenize their textures and to increase their adsorbability to the adjacent layers. The molecules of the adjacent layers should be polarizable and stratified in such a way that the free surface energies are reduced to a minimum in the plane where the layers from the two substrate surfaces meet each other. Then, this molecular unit actually is an artificial crystal with a central cleavage zone of minimum shear strength. It can be shaped cylindrically in variable dimensions, and it can be applied to any space-operating mechanism.

Such a unit may be considered a particular type of bearing, the "multi-shell space bearing." Unlike conventional bearings, the design of the multi-shell bearing is based exclusively on principles of solid state physics. The thickness of the shells (molecular layers) can vary from monolayers to multiple layers, and the molecular structure of the layers may vary from the amorphous state (Beilby-layers) over lamellar crystal configurations such as molybdenum-disulfide, to long-chain packages--even of organic compounds. The density of the oriented particles within the shells (layers) and from shell to shell, and the balancing forces among them, will prevent dissipation of the constituent particles into the high vacuum of space, and will prevent diffusion of foreign particles through the layers. The multi-shell bearing will solve both the friction problem and the sealing problem. The physical criteria for the selection and sequence of the shell molecules are their relative behavior with regard to adsorption, polarization, and surface tension.

THE SPACE TORQUE TRANSMITTER

Besides serving as bearings and sealants for removable hatches, the solid lubricant can solve the major problem of sealed power transfer from a pressurized chamber (satellite) into high vacuum (space). Based upon ideas published on the subject in technical literature, work was done to develop a device that would satisfy as far as possible the requirements peculiar to spacecraft for sealed power transfer through a pressure barrier. This device is called a Space Torque Transmitter.

The principle of the torque transmitter is sketched in FIG 32. The operating configuration of the device is shown in FIG 33. The center point of a nutating shaft, supported at either end by bearings located on the crank shaft, is theoretically at rest during rotation; while the cross sectional area of the nutating shaft through this point is nutating - but not rotating. This area is solidly connected to a bellows the other end of which is hermetically sealed to the opening of the chamber wall. Theoretically, the bellows is not affected by torque. The only stress on the bellows should be due to nutating motion of that portion of the bellows connected to the nutating shaft. This ideal situation, however, can not be realized in practice because of inevitable misalignment. The problem of misalignment is worsened by a pressure difference between the inside and the outside of the bellows.

Since pressure difference is the only critical parameter, the device was tested under atmospheric conditions with atmospheric pressure inside the bellows and higher pressure outside. The pressure was increased from zero to 15 psi in increments of 5 psi in order to obtain the increasing torque characteristic. The principles of the set-up are sketched in FIG 34 and the average torque measured is shown in the graph of FIG 35. A schematic of the torque measurement is presented by FIG 36. From FIG 37 it can be concluded that the torque with pressure outside the bellows is greater than that with pressure inside the bellows.

Modifications of the device employing two bellows at either side as shown in FIG 38, or with a membrane-type nutating element (FIG 39), did not prove advantageous. The one-bellows configuration may be considered the most adequate solution. This type of torque transmitter was tested with rotational speeds up to 1000 rpm.

The angle of the nutating shaft to the centerline of the driving shaft was recognized as another important parameter. An angle of about 10 degrees was found the optimum for varying rotational speeds. The testing of other parameters such as material of bellows, length, diameter, thickness, and number of corrugations was delayed because of long-term sample procurement. In the meantime, some torque transmitters are being built with varying bellows parameters. Presently, one of these torque transmitters (FIG 40) is being installed in a vertically mounted vacuum extension system (FIG 41). These torque transmitters will be tested in the near future under a high vacuum of 10^{-7} Torr one side as a combination adequate for space application.

Smaller scale modifications of this type of torque transmitter were used successfully in connection with the oscillating disc tester. The modified devices provided the outside-operated starting mechanism for the oscillating disc and the loading mechanism under high vacuum.

The torque transmitter device developed under this project may be recommended for space application with the reservation that the operational qualities of the bearings are limited. The advancement of knowledge of the frictional mechanism according to the ideas outlined in the previous sections would solve even this problem, and would probably eliminate the relatively complicated mechanical design of the torque transmitter. The prospect emphasizes the need for further studies of the friction phenomenon in the direction suggested in this report.

APPENDIX A

ABSTRACT OF THE RESULT OF THE CBS CONTRACT CONCERNING PRINCIPLES OF DRY LUBRICANT COATINGS IN BALL BEARINGS FOR SPACE APPLICATION CONTRACT NUMBER DA-10-020-506-ORD-5171

The principal purpose of this study was to determine the relationship between the thickness of dry lubricant coatings and the friction of commercial 440 stainless steel ball bearings lubricated with these coatings in a vacuum in the order of 10^{-6} Torr or better under varying rotational speeds.

The test bearings having stainless steel balls of 1/16-inch diameter were connected to the rotor of a small electric motor which had been mounted in an evacuated glass tube – the starter of which was placed outside the glass tube. The testers have been baked out at 350°C for a period of approximately 12 hours at low pressures.

Friction has been determined from running and starting torque derived from motor starting voltage, from armature slip below synchronism, and from coast time. The running speed in vacuum has been determined by stroboscope.

To accomplish the stated objective the following work plan has been pursued:

(1) Deposition of evaporated silver of varying thicknesses on groups of bells using a controlled thickness of nichrome between base and silver. Silver thicknesses vary between 100Å and 2000Å. Selective tests with the addition of molybdenum disulphide in fine particle form.

(2) Determination of the silver thickness and nichrome coatings through the use of special weighing methods and techniques of optical transmission.

(3) Assembly of coated stainless steel balls of 1/16-inch diameter in bearings and testers suitable for rotational drive on continuously-pumped vacuum systems.

(4) Sealing the testers to vacuum systems having meter-cooled baffles and bakeable traps, evacuating to a pressure of 10^{-6} Torr or better, baking out at 350°C for 14 hours, cooling, and then operating for a period of time up to 100 hours. During this time, periodical recording of starting torque, speed, coast time and pressure.

(5) Evaluation of the frictional characteristics as a function of the silver film thickness.

Following are the conclusions of major interest: A definite correlation exists between the thickness of silver films evaporated upon ball surfaces and the friction of bearings in high vacuum. This is apparent by FIG 42 where the results of five test groups are plotted with the reciprocal of coast time substituted for coefficient of friction. A similar graph (FIG 43) is given by Bowden and Tabor on indium-plated tool steel. The striking similarity between the two plots is of interest in so far as some major differences due to the substrate material and surface finish should be expected. Ball bearings in the tests of this study had surface finishes of approximately 1-2 microinch AA while the tool steel plates were probably at best 16 microinch AA. In addition to that, the indium tests were not conducted under vacuum conditions.

Dry or solid film lubricants provide anti-friction properties under conditions of boundary lubrication. This action contrasts with the action of conventional oil and grease lubricants which exhibit anti-friction properties under hydrodynamic conditions where an appreciable lubricant film is maintained between mating surfaces. It can be assumed that in utilizing a thin metallic film as a lubricant, this film must, in addition to other properties, possess an optimum thickness in order to prevent the shearing action of the surface asperities against each other. Furthermore, it is particularly important to prevent, or at least to minimize metal-to-metal contact in high vacuum in order to avoid cold-welding of mating surfaces to each other. It should follow that the smaller the surface summits the thinner the lubricant film may be.

To satisfy other requirements, the metal film should be of low shear strength, and have a high adherence to the base material. Inasmuch as low-shear-strength solid materials have a high susceptibility to plastic deformation, it would be theoretically desirable to use metallic films as thin as practicable so as to minimize the effects of plastic deformation, and to permit the film to deform and reform elastically with the base material.

For this investigation, thin films of vapor-deposited silver were selected for study. Silver has been extensively investigated for use in vacuum and has high thermal and electrical conductivity, fairly low shear strength, low vapor pressure and a low coefficient of friction against steel.

Molybdenum disulfide was selected for testing as an additive to the silver film due to its superior lubricant properties, low vapor pressure, and its ability to withstand elevated temperatures.

The position results obtained from scattered tests in which the evaporated silver film was impregnated with molybdenum disulfide, emphasize the need for a broad program of research, development, and reliability testing in this particular field of solid lubricant development.

APPENDIX B

ABSTRACT OF THE FINAL REPORT ON THE CVC-CONTRACT CONCERNING THE SEALING OF REMOVABLE HATCHES FROM ATMOSPHERIC PRESSURE TOWARD AN ULTRA-HIGH VACUUM CONTRACT NO. DA-30-069-ORD-2953 (HATCH SEAL STUDY)

INTRODUCTION - CONTRACT OBJECTIVE

In the field of vacuum technology are several unsolved problems in connection with making and maintaining tight seals, particularly if the seals are subjected to wide ranges of environmental conditions. It is felt that the general problem of sealing is both a material and a mechanical problem. The material side concerns the selection or development of adequate sealants in regard to outgassing, diffusion, etc. The mechanical requirements are dictated by the specific application. On a space station, the main characteristics required of removable hatches are absolute sealing to avoid air loss, and ease of manual handling. The basic idea of this contract was to determine general design principles satisfying those requirements.

In this report the content of the earlier reports is summarized very briefly, and emphasis is placed on observations made on the experimental results and on conclusions and recommendations that can be drawn from the limited amount of data obtained up to the contract termination date.

THEORETICAL CONSIDERATIONS - TECHNICAL APPROACH

The sealing process is a matter of close material contact. The study therefore will be concerned with what occurs at the interface between adjoining surfaces and determining what conditions most affect the leakage of gas across this interface. Obviously, the magnitude and direction of applied sealing forces will be a major item; in addition, such factors as surface conditions and hardness will be significant. Microscopic study of surfaces shows that contact between adjacent surfaces occurs at the tips of surface irregularities and the contact area is a relatively small percentage of the total area, even under high normal loads, leaving valleys through which leakage can occur. Plastic deformation of a sealant must be accomplished to fill these valleys.

In the Preliminary Study Report it was shown that elastomer materials should not be used in this study since permeation through them would be much greater than the smallest interface leakage anticipated to be measureable; and that therefore a metallic sealant would be used in the experimental work. It is advisable to use metal from the standpoint of temperature tolerance. No temperature requirements were specified in this work, but testing of this parameter is a necessity.

A conical sealing surface for the hatch was suggested in the "Statement of Work". The advantages of this would appear to be the contribution of a tangential component of the applied sealing force that would tend to fill surface irregularities by causing surface flow, and the positioning of the hatch with respect to the opening. Whether any improvement of the sealing effect would result from the inside pressure of the space station acting on the conical surfaces would depend on the coefficient of friction of the mating surfaces; and since this will probably be very large under vacuum conditions, the likelihood of any improvement would be very small.

The suggested work on conical surfaces included:

1. Investigate cone angles from 30° to 80° in 10° increments to determine an optimum angle; this work to be done on 6" diameter hatches.

2. Using the optimum angle, make and test a series of hatches up to 20" in diameter in 2" increments.

Measurements are to be made on leakage rates, sealing forces and hatch removal forces with extrapolations to weightlessness for the latter.

A further suggestion was made to investigate an approach involving an expanding disc-type seal being developed in small-size valves at C. V. C. In this design a conical disc is made to expand outward and seal against the inside surface of a cylinder. A change in scope of the contract which would allow work on this approach was discussed; however, it did not materialize before the contract was terminated.

EXPERIMENTAL EQUIPMENT

The equipment designed and built for the test program consists essentially of the test flanges, a hydraulic cylinder, a vacuum system, leak detector and necessary gauging and controls. It is depicted diagrammatically in FIG 44.

A hydraulic press was considered a more satisfactory means of controlling and measuring forces than were bolts and torque wrenches which can introduce large errors through unknown friction coefficients. The cylinder is large so as to provide the forces estimated to be required.

Several possible configurations could be used on the conical flanges. The one selected will give a constant and measureable sealing face area regardless of the amount of gasket deformation. The width across the seal is 1/8 inch on all tests of the initial series. This may be changed if test results indicate such to be advantageous. A clamp ring is provided to hold the gasket securely during initial deformation, and to provide a pilot cone for achieving approximate alignment of the sealing surfaces on initial approach. This ring is also used to direct the helium along the outside of the seal and to insure 100% concentration of helium in this region.

The leak detector is a CEC Model 24-210A mass spectrometer type helium leak detector capable of detecting leakage rates as low as 1×10^{-10} atm cc/sec of helium and as high as 1×10^{-5} atm cc/sec. Leakage rates above 1×10^{-5} atm cc/sec seem high to be of prime interest in this work.

EXPERIMENTAL WORK

In the planned experimental work several series of tests were anticipated. The first series was undertaken with the objectives of establishing procedures and techniques for achieving reproducible and reliable data, and also of selecting a suitable sealant material which could be used in all subsequent tests. The next series would investigate the range of cone angle, and the one after that, a series of larger hatches made with an optimum cone angle.

It is unfortunate that just as the fruitful part of the work was getting underway it was interrupted by termination of the contract. As a result, the "technical findings" are meager and few valid conclusions can be drawn at this point. However, some of the results do have significance.

Approximately 18 tests were initiated on the first series before termination of work. Though more work should be done on this series some interesting behavior characteristics are now being recognized.

Of the different sealant materials tested, aluminum sheet, .051"-thick, annealed and polished, has produced the most satisfactory seals, and at a much lower force than required for other materials. No extensive materials evaluation was conducted but tests were made on (.0035") aluminum sheet, in both annealed and hardened conditions on copper sheet, and on the flanges with no sealant between them. The flange faces were highly polished.

In several tests, the same gasket was resealed five times. The procedure used was to increase the sealing force in increments, allowing the vacuum system to come to equilibrium and recording the leakage rate across the seal for each sealing force. Force was increased until leakage was less than that detectable by the helium mass spectrometer leak detector; then the force was decreased in increments and leakage rates again recorded. This constituted a cycle. Of the five cycles run on one of the gaskets, considerable variation occurred, but in all cases a tight seal was achieved at a force of 288 lb/linear inch of seal. During the latter half of the cycle, during which force was reduced, leak tightness was maintained at much lower sealing forces than were required on the first part of the cycle. At present no particular significance is attached to this behavior.

One observation that did appear significant was the fact that on initial gasket deformation, a tight seal was achieved at the relatively low sealing force of 102 lb/inch of gasket. This occurred when the top face of the gasket was indented by the sharp edge at the bottom of the conical surface on the male flange, while at the same time, the bottom face of the gasket was indented by a similar sharp edge on the female flange. In this condition, there is a similarity to the well-known knife-edge seal which by its nature requires low sealing forces. The gasket was not fully shaped to the flange faces. Additional force, therefore, fully formed the gasket to the conical configuration, and the seal was transferred from the indentations to the flat surfaces. During the transition, leakage increased, but then decreased again at higher forces. On succeeding cycles there was no sealing at the indentation--and thus, no initial tight seal at a low applied force. There did, nevertheless, appear to be a tendency toward lower required forces for a given leakage rate on successive cycles.

Among other observations, it was noted that momentary leakage bursts occurred during force changes, no doubt caused by slippage at the interface; also there appears to be some metal creep at constant force since an overnight reduction in leakage rate was observed while sealing force was held unchanged. Further observations of this behavior will be valuable.

On the first test employing copper, it was noted that when small radial scratches were present on the sealing surfaces there was no tendency for the metal compressed between the flanges to flow into the scratches and seal them, despite the force of 2550 lb/linear inch of seal.

When no gasket was used, forces up to 1350 lb/linear inch of seal were required to make a tight seal. When a thin (.0035") aluminum gasket, annealed and polished was used, the required force dropped to 818 lbs/linear inch of seal. When a thicker (.051") aluminum gasket was used this force dropped further to 288 lbs/linear inch of seal. A possible explanation for this trend is that the flanges cannot be made to match perfectly and some deformation is required to make them seal. A thin gasket will take up some of this deformation; a thicker one will take up more, and at a reduced applied force. This indicates that as flange diameters become larger, thicker gaskets may be required for larger machining tolerances.

There was no surface damage to flanges or gaskets even at the highest loads applied (2550 lb/linear inch), so it appears that a condition where cold-welding of the surface occurs was not approached. Higher temperatures may be required before cold-welding becomes a problem.

Presently there is insufficient evidence to reach a conclusion about the merits of the conical seal. The ability to make a seal with reasonable force on a 6" diameter hatch was demonstrated, and results of initial effort warrant continuation of the experimental program, as originally planned. Evaluation of the first tests gives an indication that there may be significant areas of investigation that were not heretofore considered.

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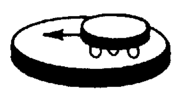
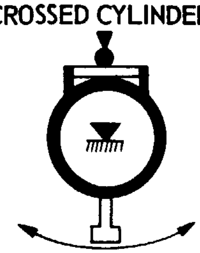
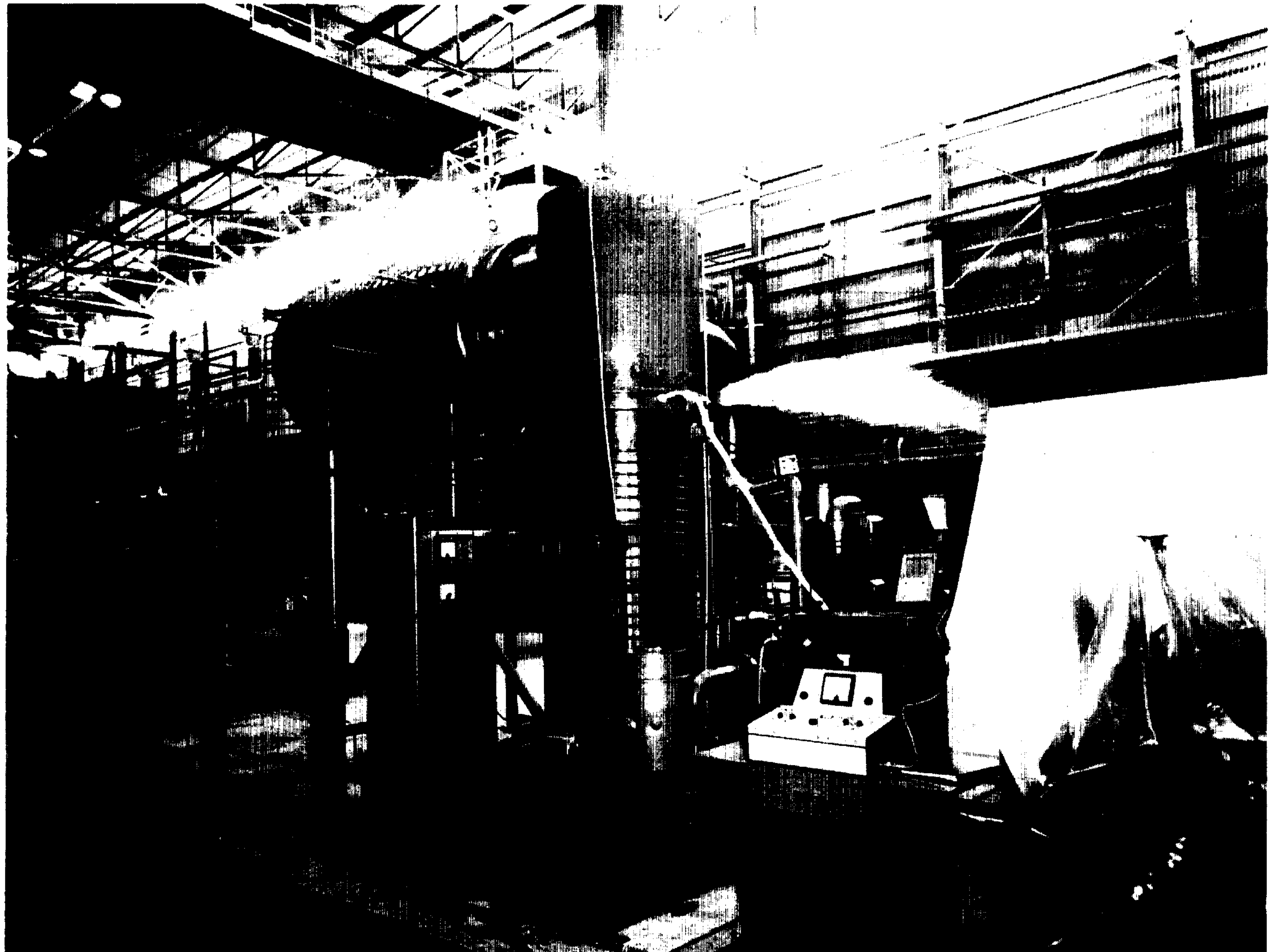
TABLE 1. SUMMARY OF FRICTION TESTS

TEST PRINCIPLE	SAMPLE CONFIGURATION	NUMBER OF TESTS	HARD METALS	SOFT METALS	NON METALS
INCLINED PLANE (AERIAL CONTACT)	SLIDER  BASE PLATE	54		BRASS PHOSPHOR BRONZE ALUMINUM ALUMINUM BRONZE	
SLIDING TRIPOD (3 POINT CONTACT)	TRIPOD  BASE PLATE	35	440 – C – SS STELLITE NICKEL T – 5 HIGH SPEED	BRASS PHOSPHOR BRONZE ALUMINUM ALUMINUM BRONZE	GLASS PYROCERAM
OSCILLATING DISK (1 POINT CONTACT)	CROSSED CYLINDERS  PENDULUM	90	440 – C – SS STELLITE NICKEL CIRCLE – C HASTELLOY		GLASS PYROCERAM SAPPHIRE



MTP-P&VE-P-62-4

FIGURE 1. HIGH ALTITUDE SIMULATION SYSTEM AT MSFC

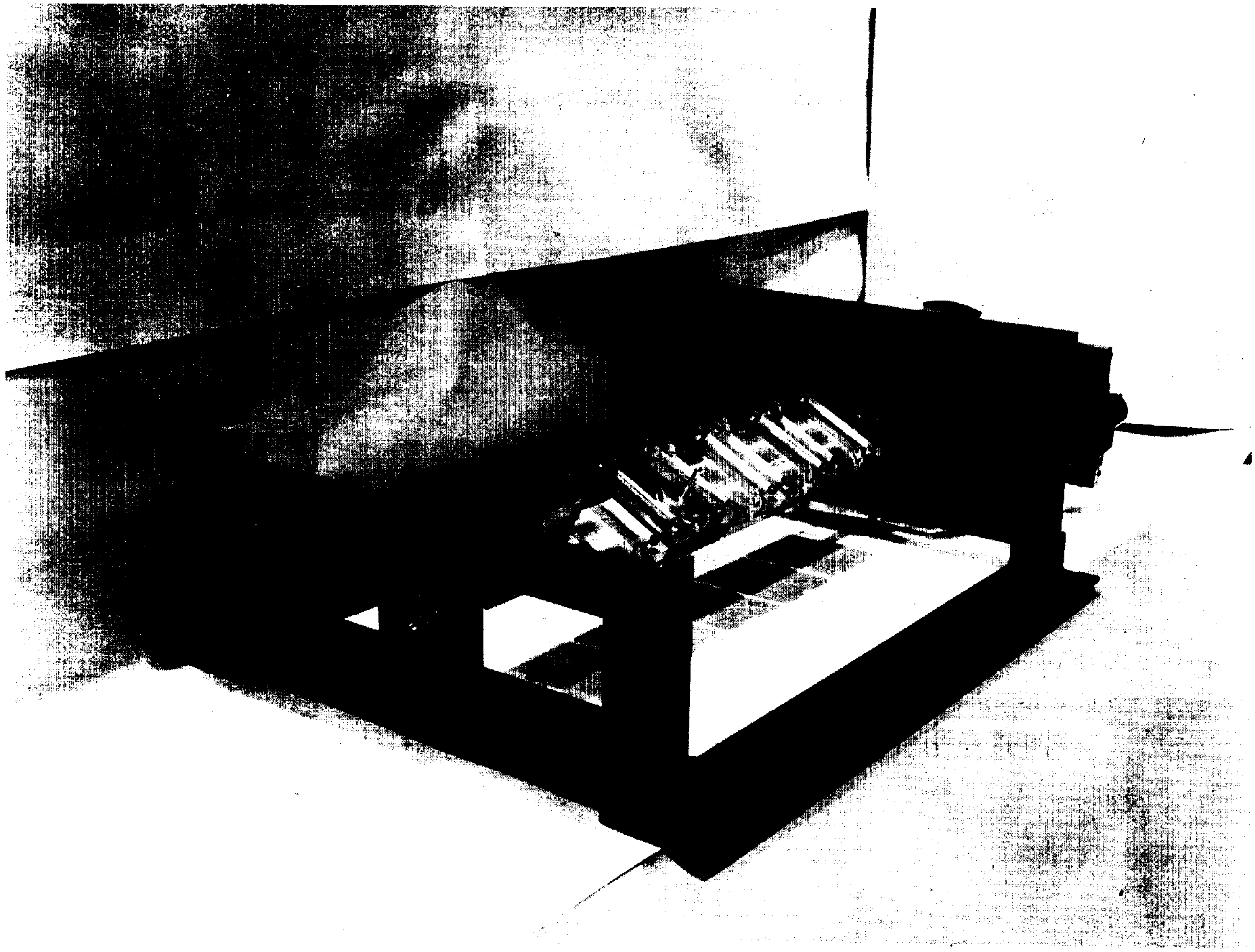
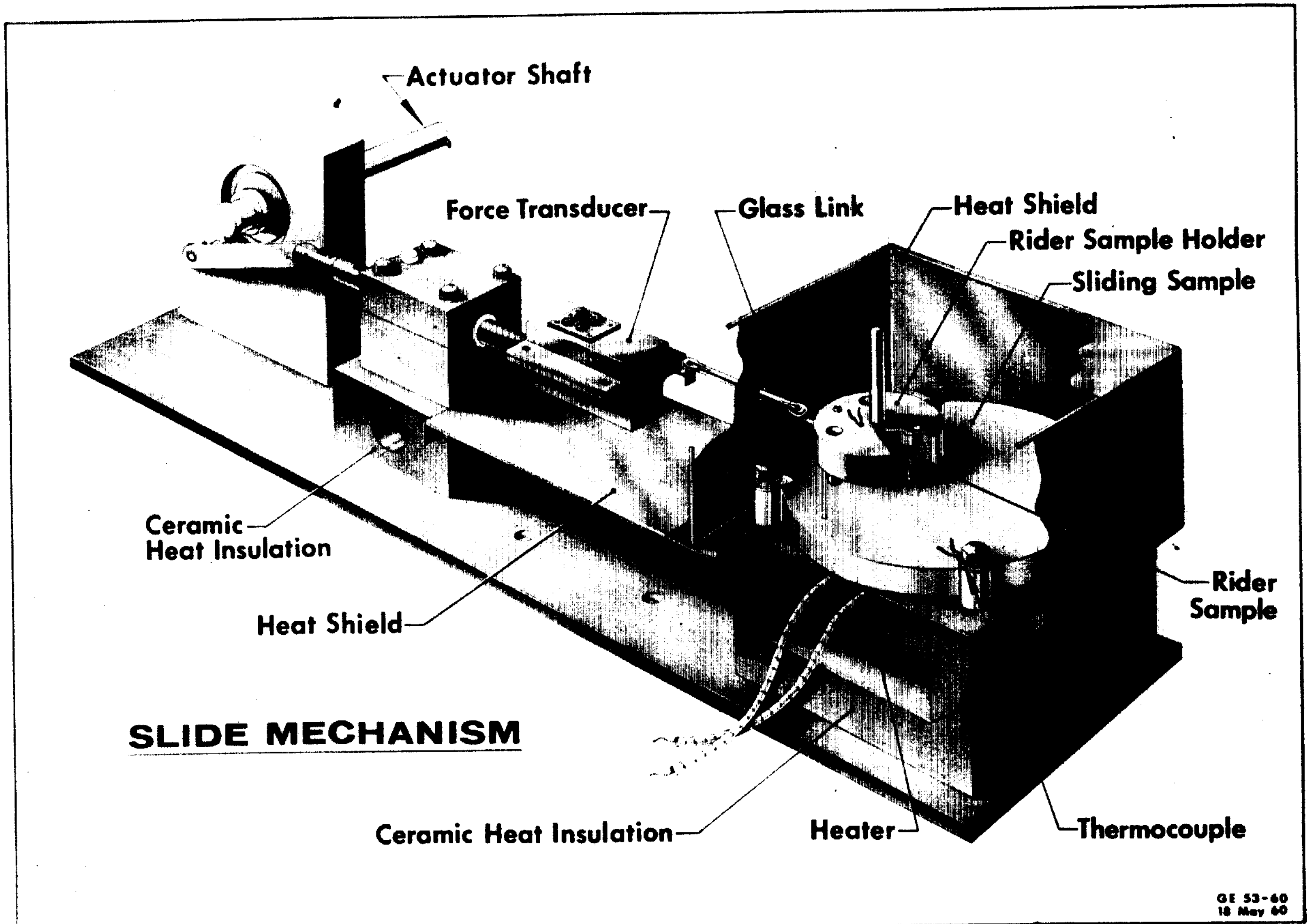
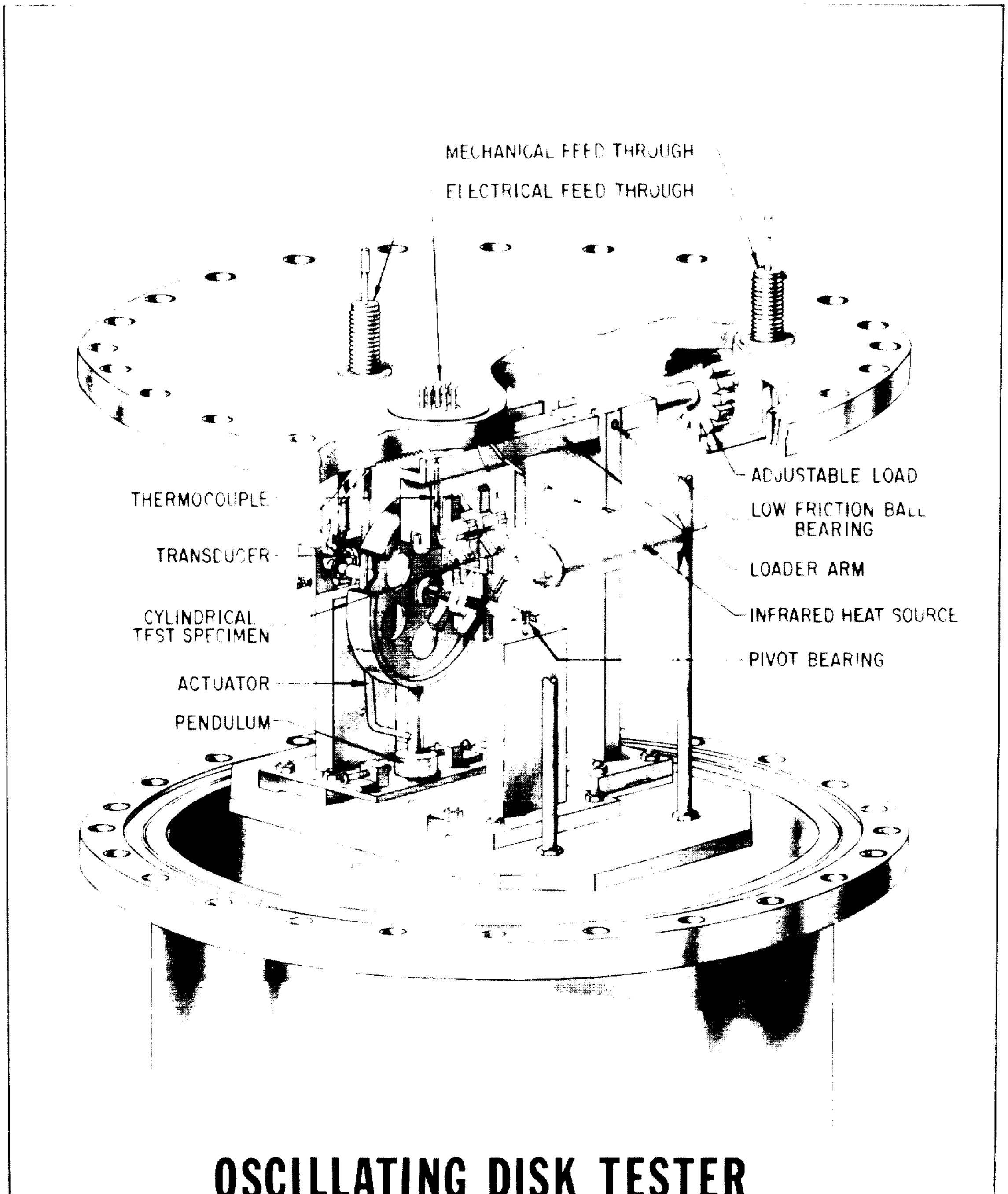


FIGURE 2. INCLINED PLANE



MTP-P&VE-P-62-4

FIGURE 3. SLIDE MECHANISM



MTP-P&VE-P-62-4

FIGURE 4. OSCILLATING DISK TESTER

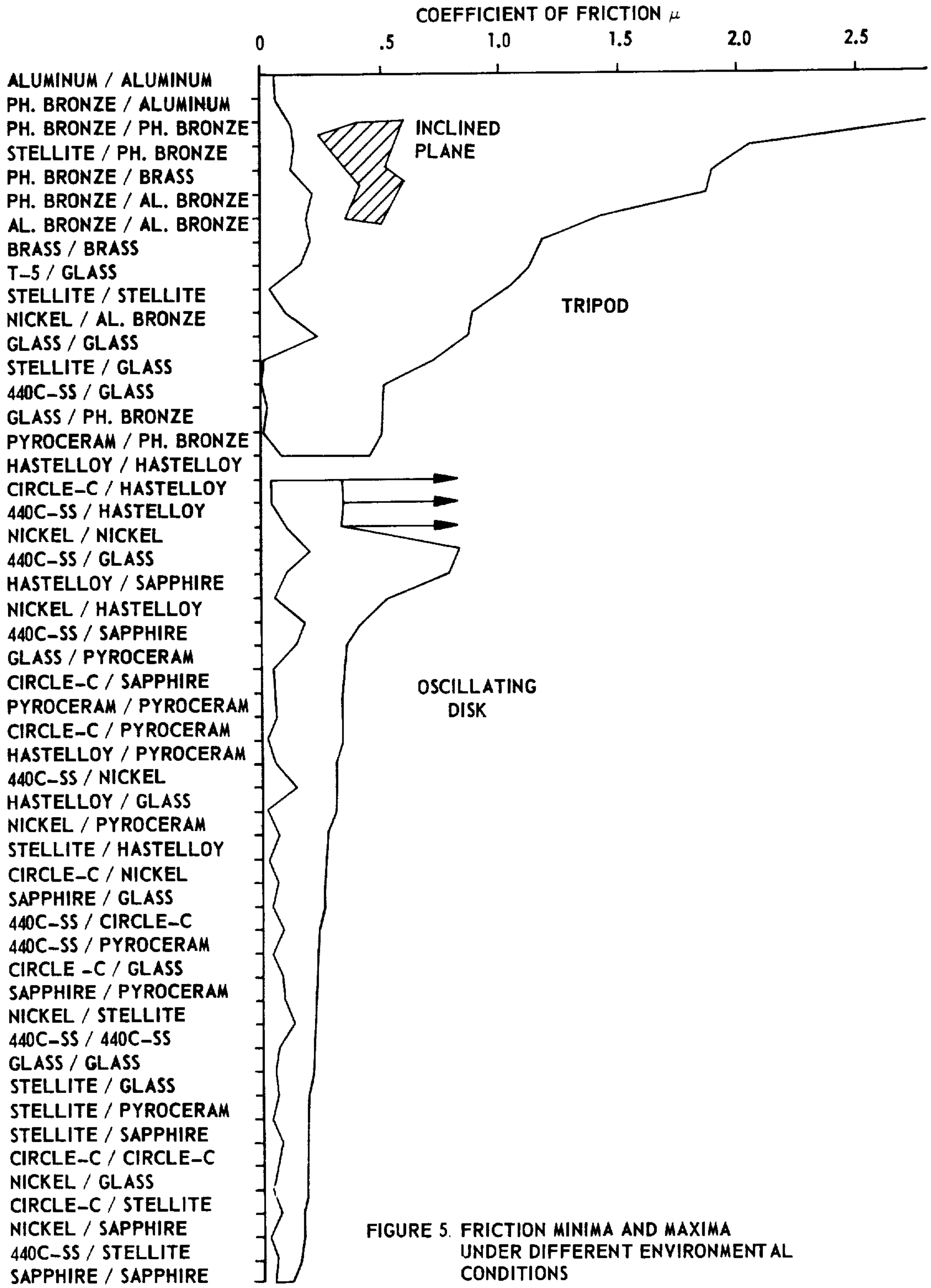


FIGURE 5. FRICTION MINIMA AND MAXIMA UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

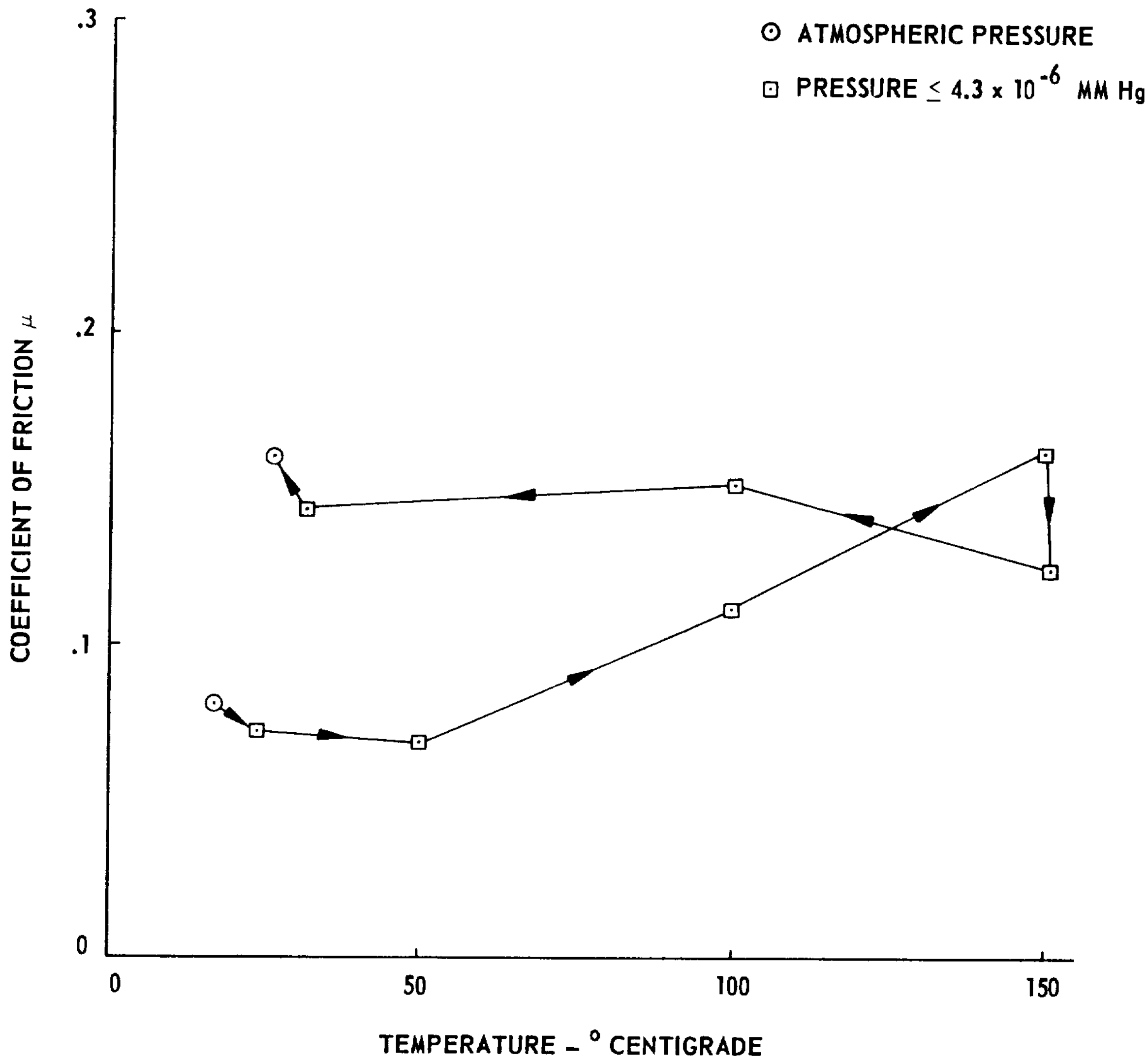


FIGURE 6. COEFFICIENT OF FRICTION VS. TEMPERATURE: 440 ss ON 440 ss

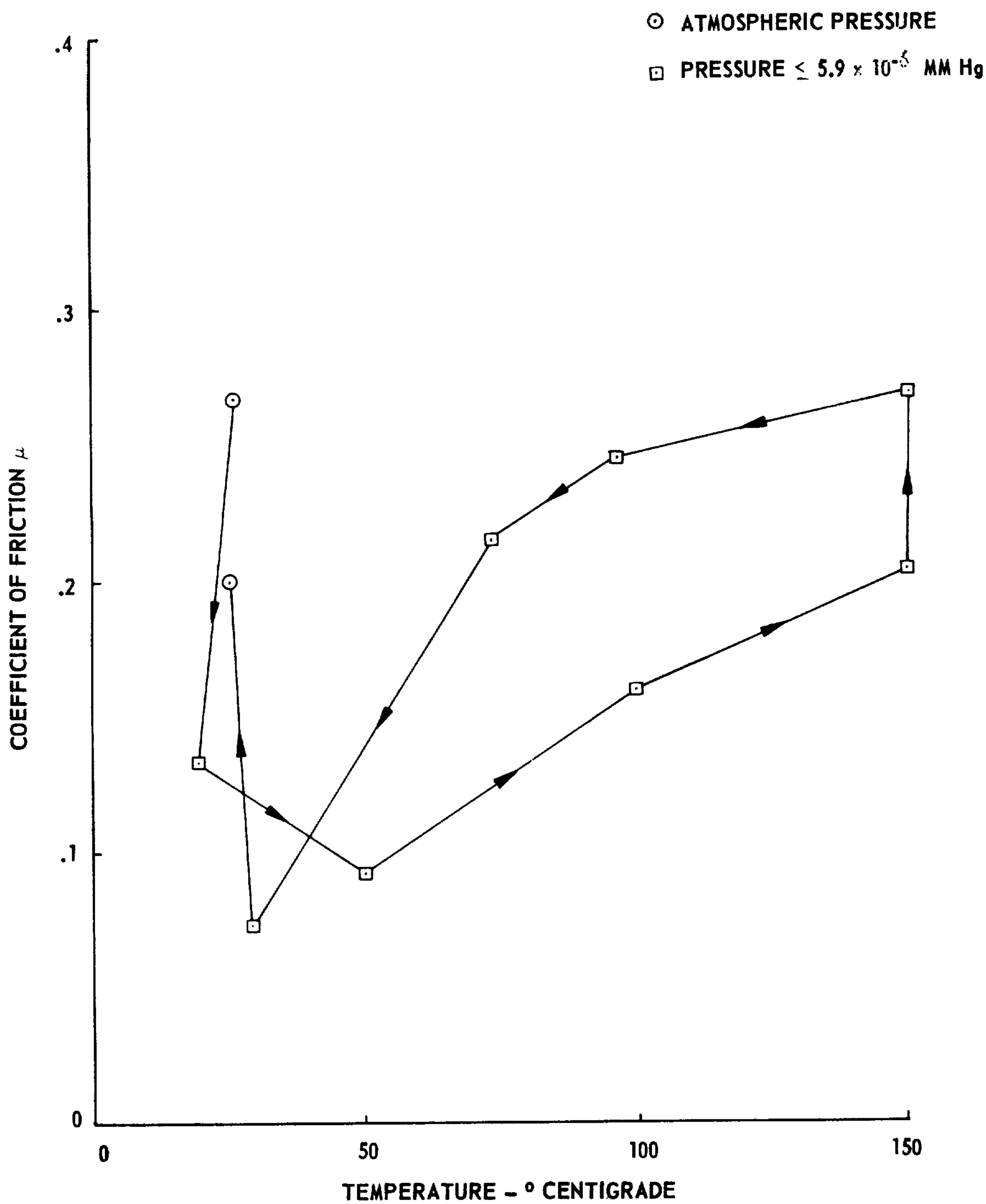


FIGURE 7. COEFFICIENT OF FRICTION VS. TEMPERATURE: PYROCERAM ON NICKEL

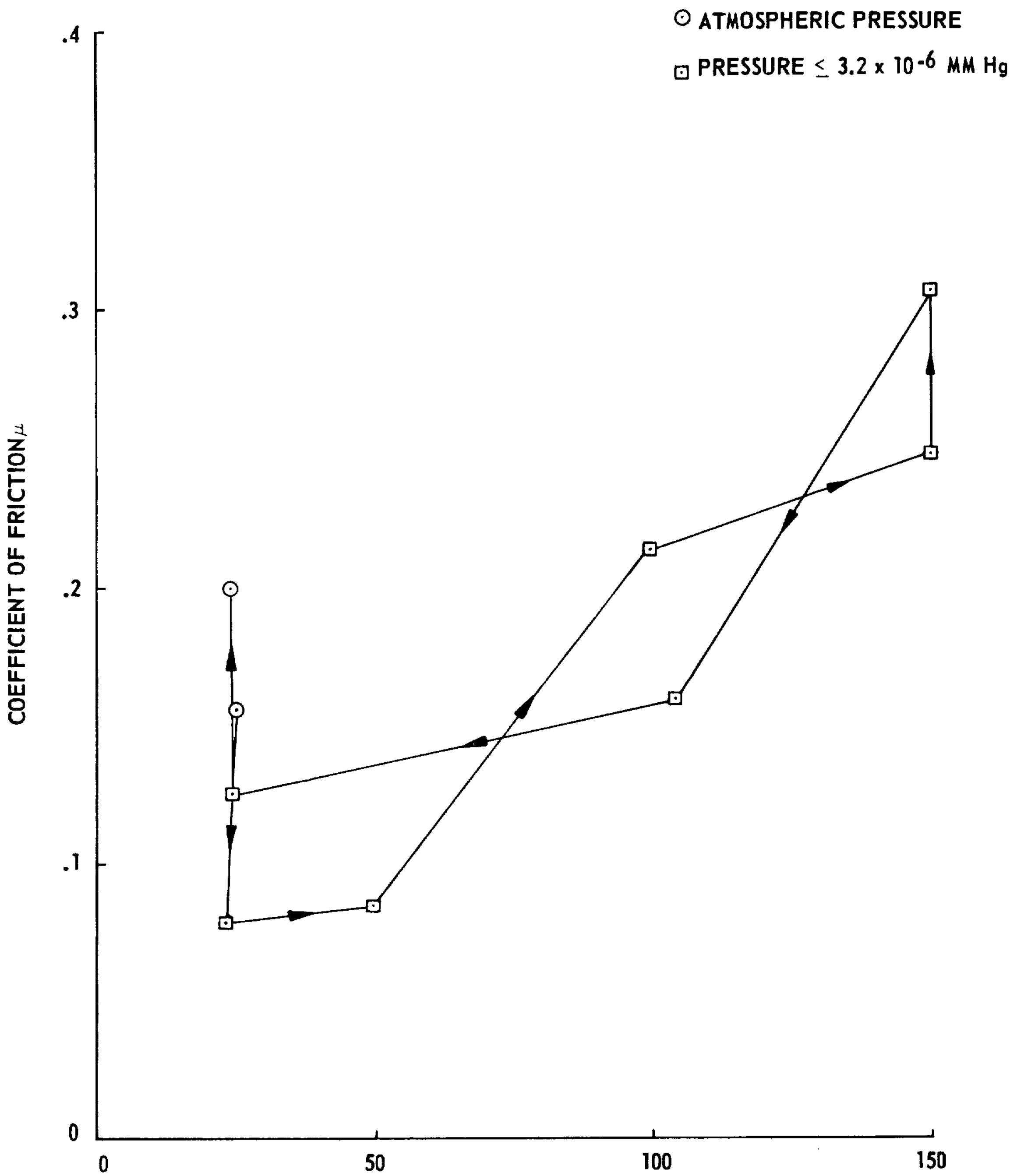


FIGURE 8. COEFFICIENT OF FRICTION VS. TEMPERATURE HASTELLOY ON GLASS

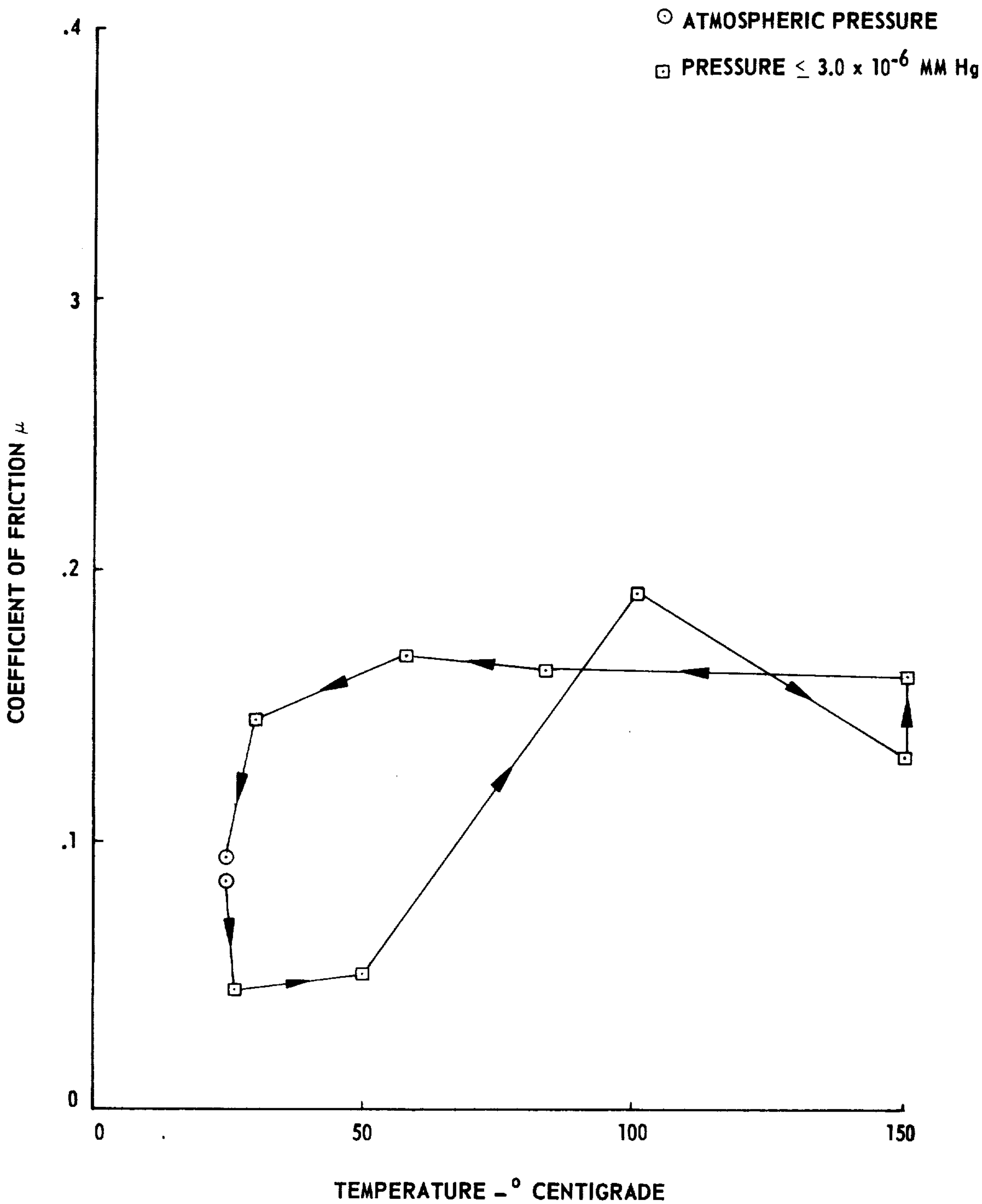


FIGURE 9. COEFFICIENT OF FRICTION VS. TEMPERATURE PRYOCERAM ON STELLITE

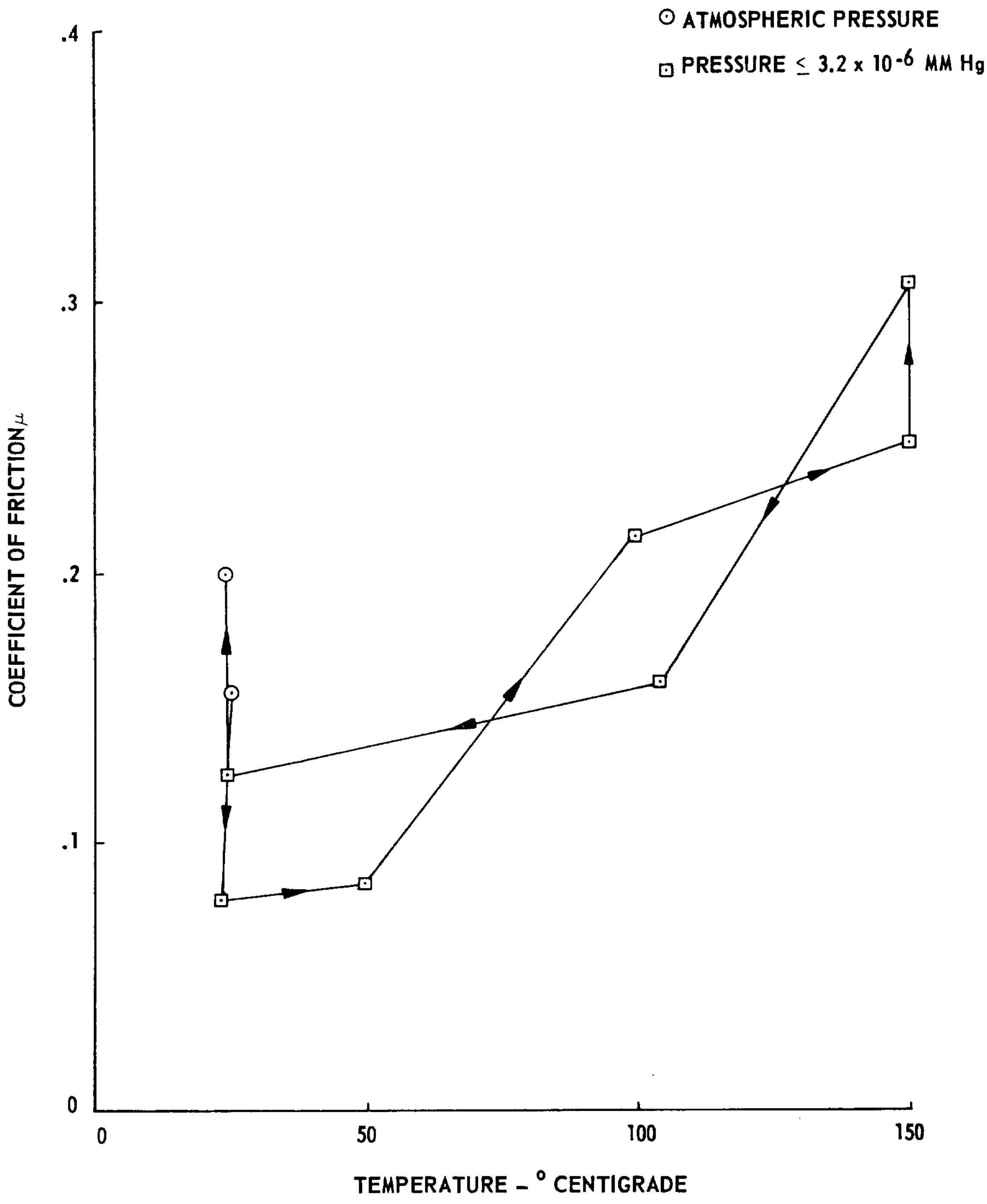


FIGURE 8. COEFFICIENT OF FRICTION VS. TEMPERATURE
HASTELLOY ON GLASS

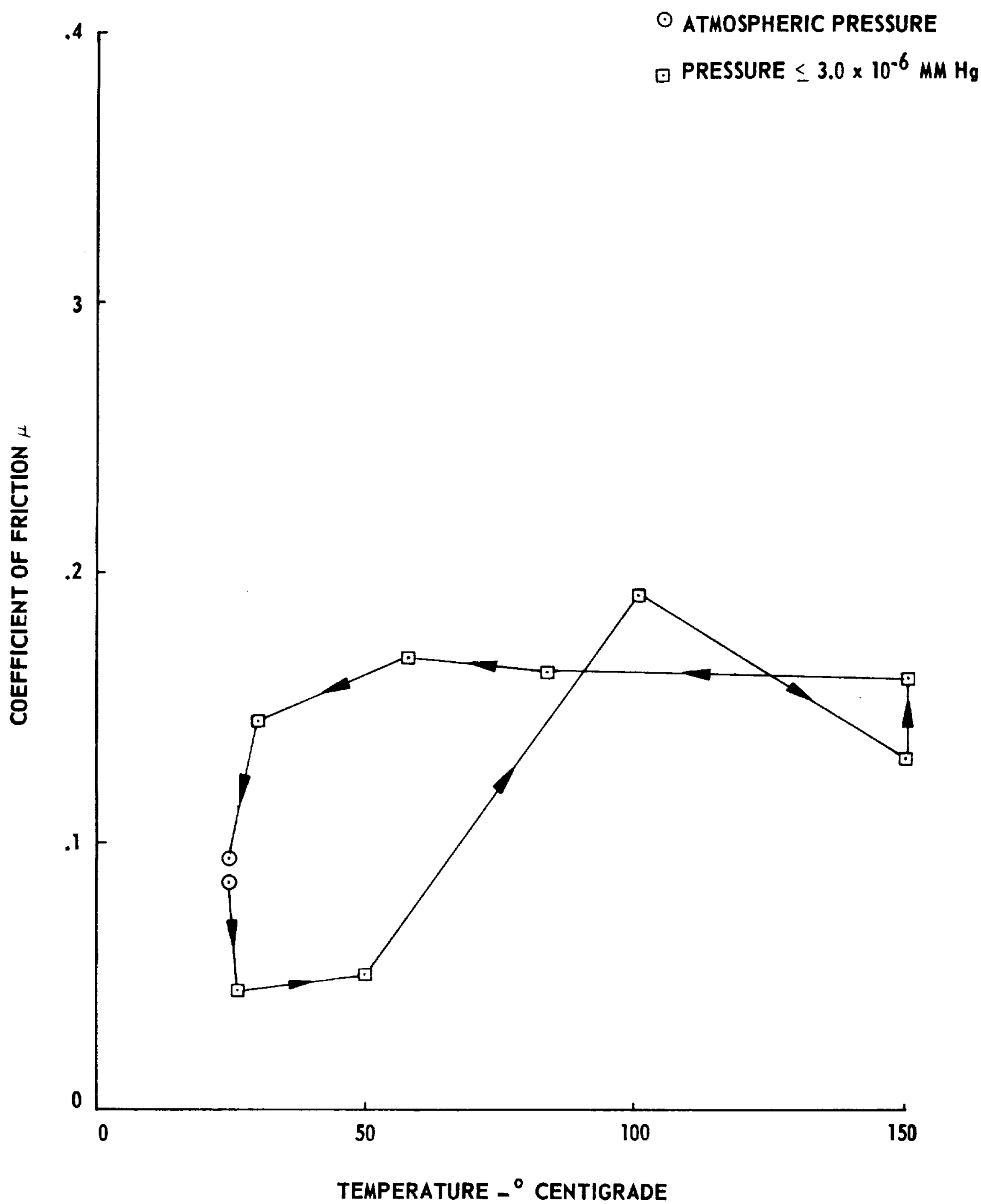


FIGURE 9. COEFFICIENT OF FRICTION VS. TEMPERATURE
PRYOCERAM ON STELLITE

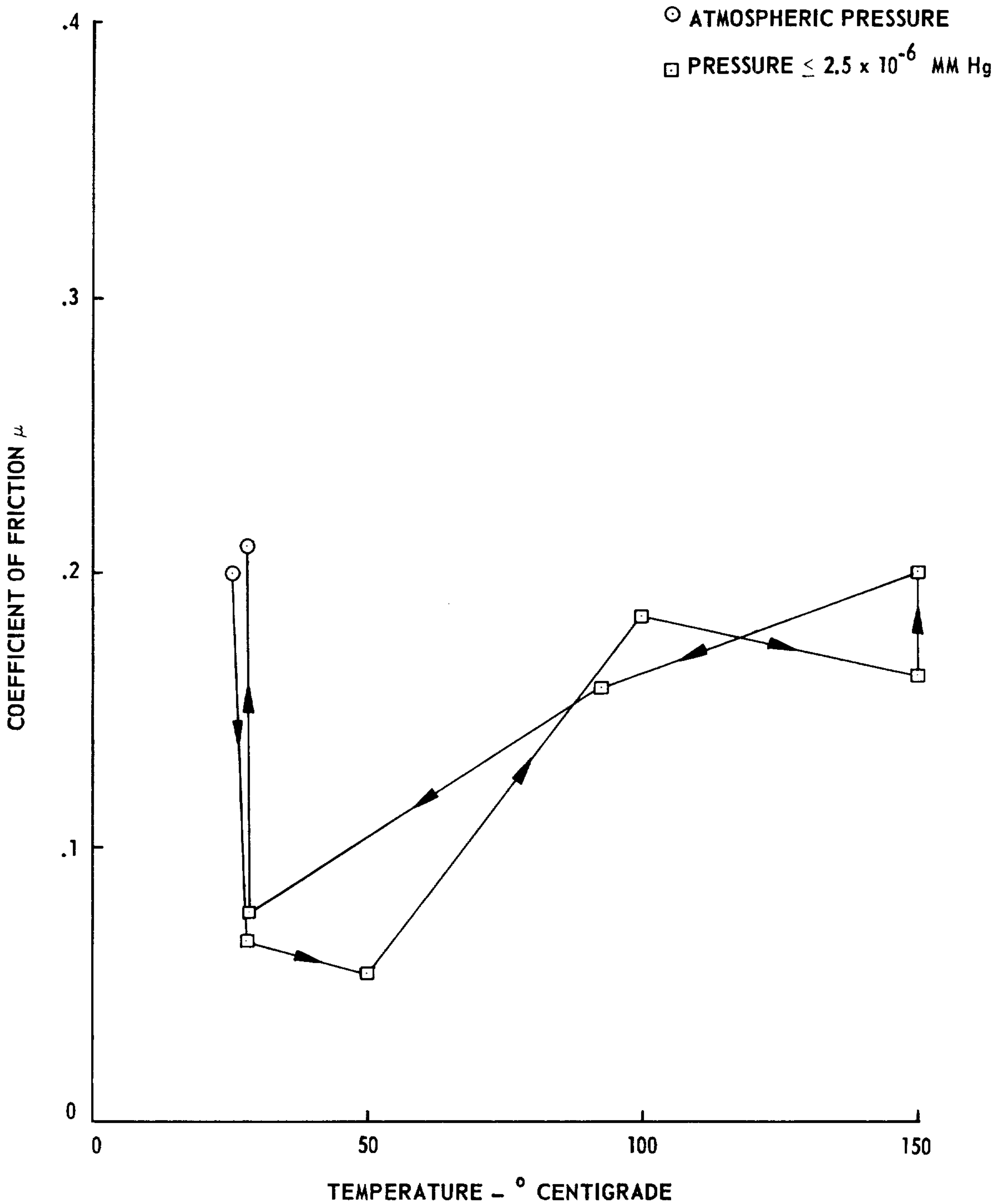


FIGURE 10. COEFFICIENT OF FRICTION VS. TEMPERATURE
GLASS ON GLASS

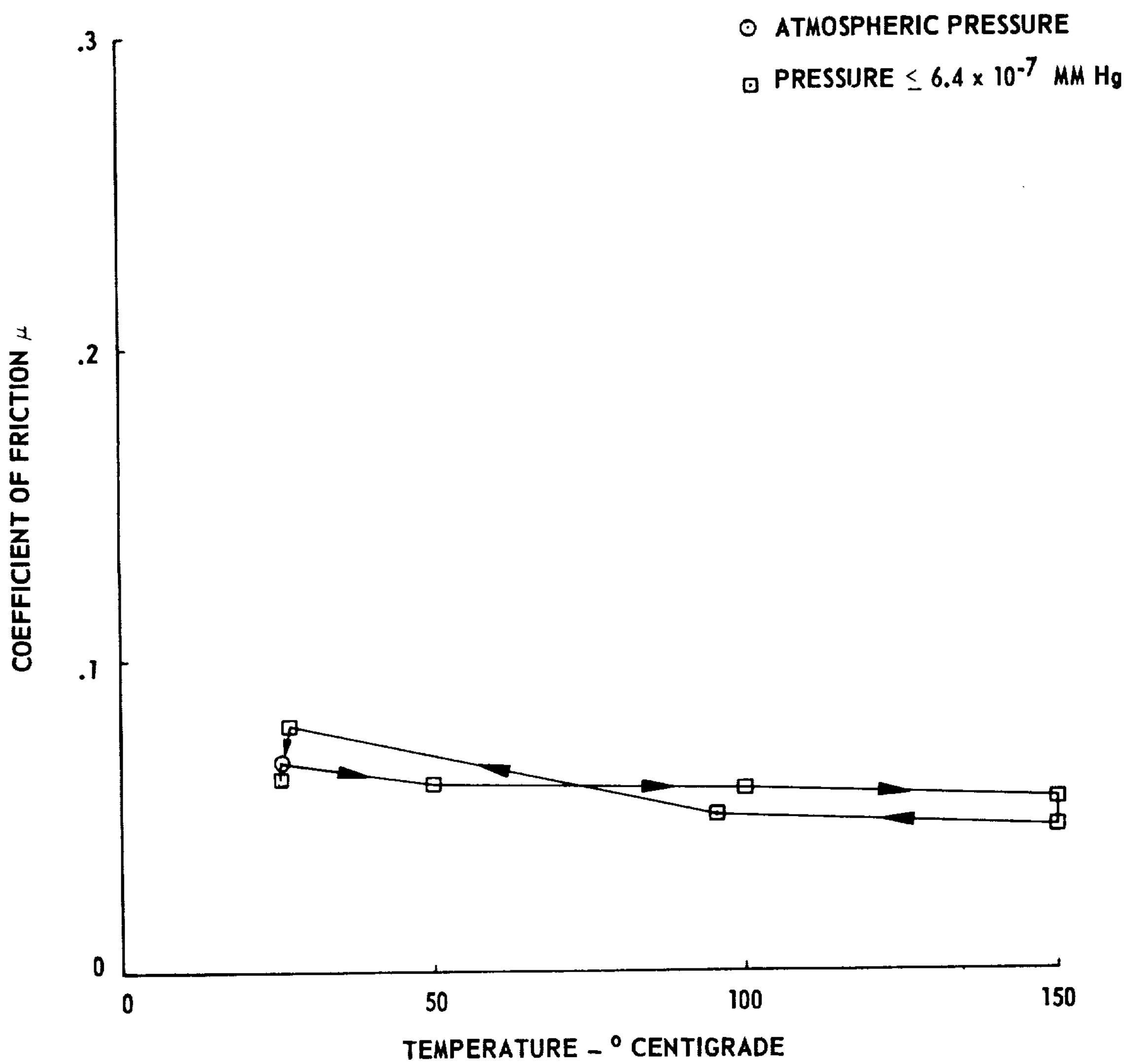


FIGURE 11. COEFFICIENT OF FRICTION VS. TEMPERATURE

SAPPHIRE ON CIRCLE-C

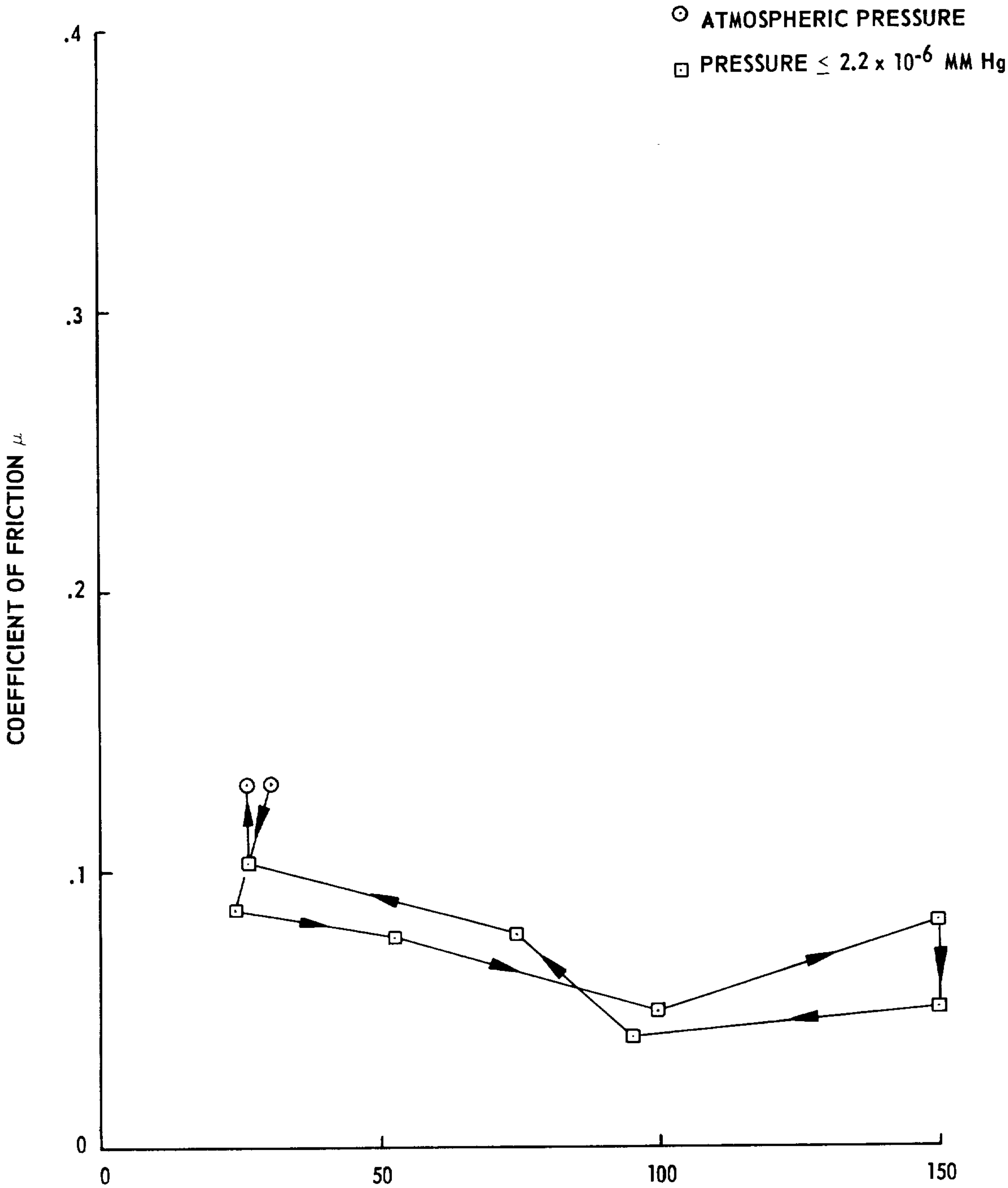


FIGURE 12. COEFFICIENT OF FRICTION VS. TEMPERATURE

SAPPHIRE ON NICKEL

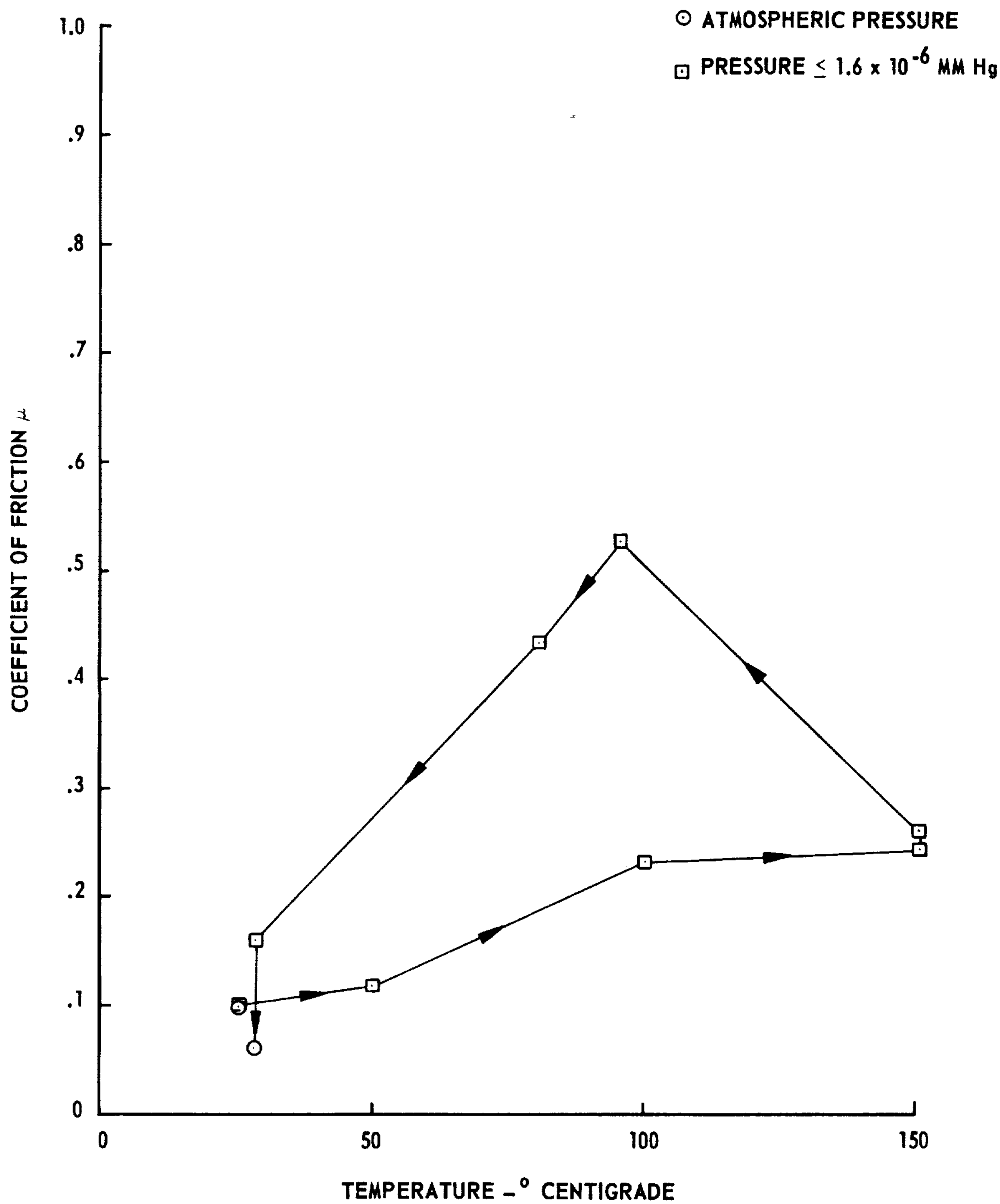


FIGURE 13. COEFFICIENT OF FRICTION VS. TEMPERATURE

SAPPHIRE ON HASTELLOY

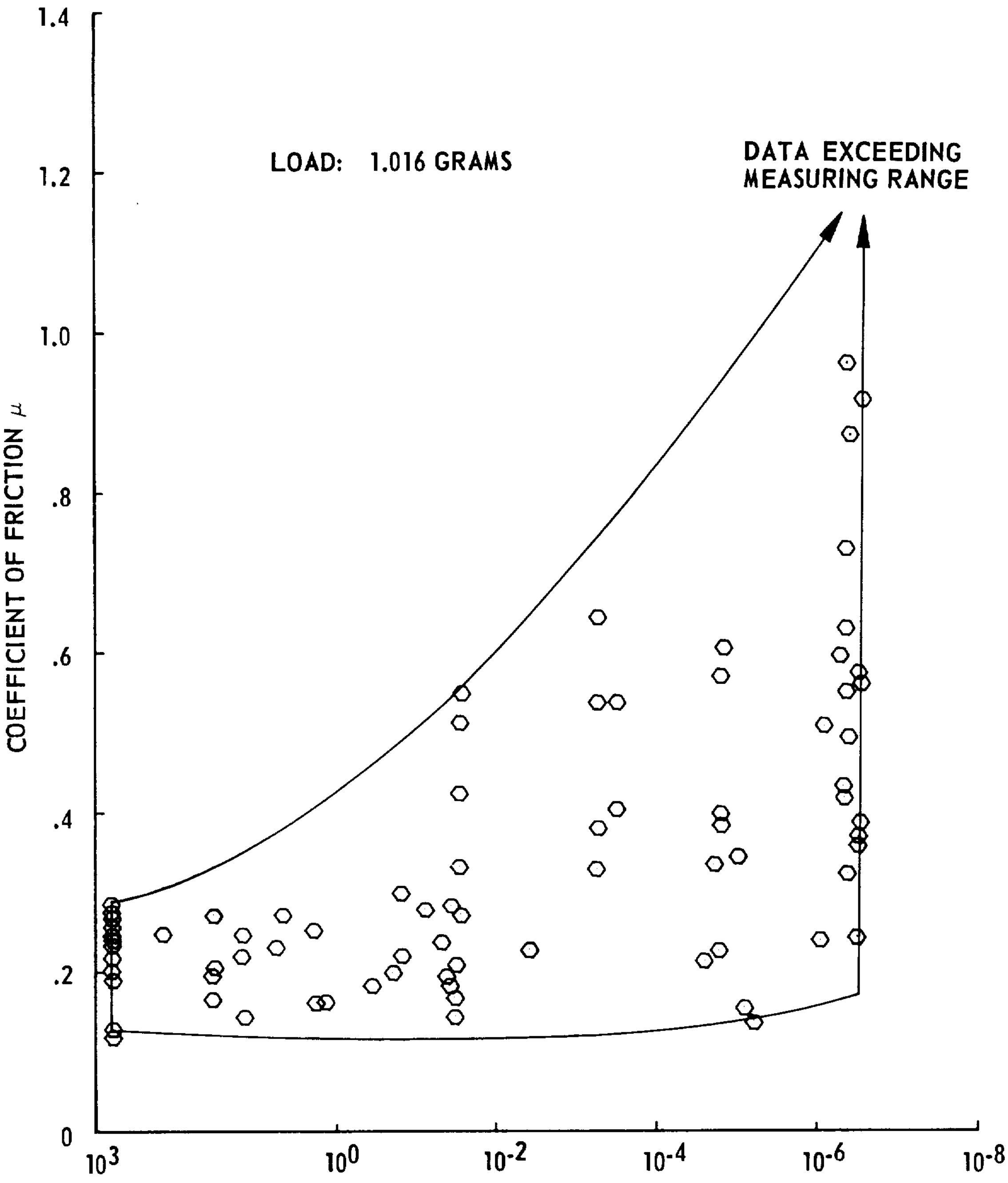


FIGURE 14. COEFFICIENT OF FRICTION VS. VACUUM

HASTELLOY ON NICKEL

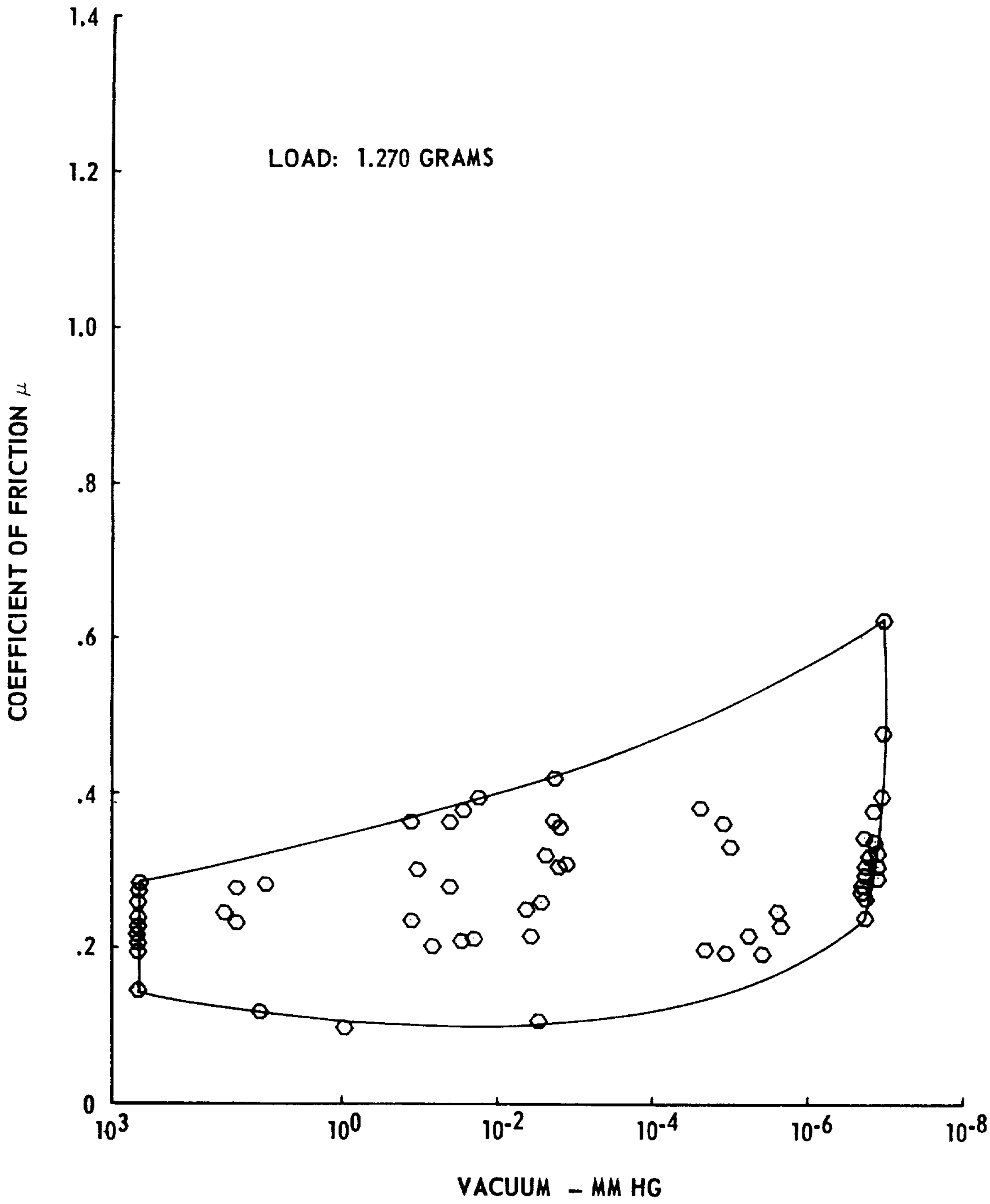


FIGURE 15. COEFFICIENT OF FRICTION VS. VACUUM

CIRCLE C ON NICKEL

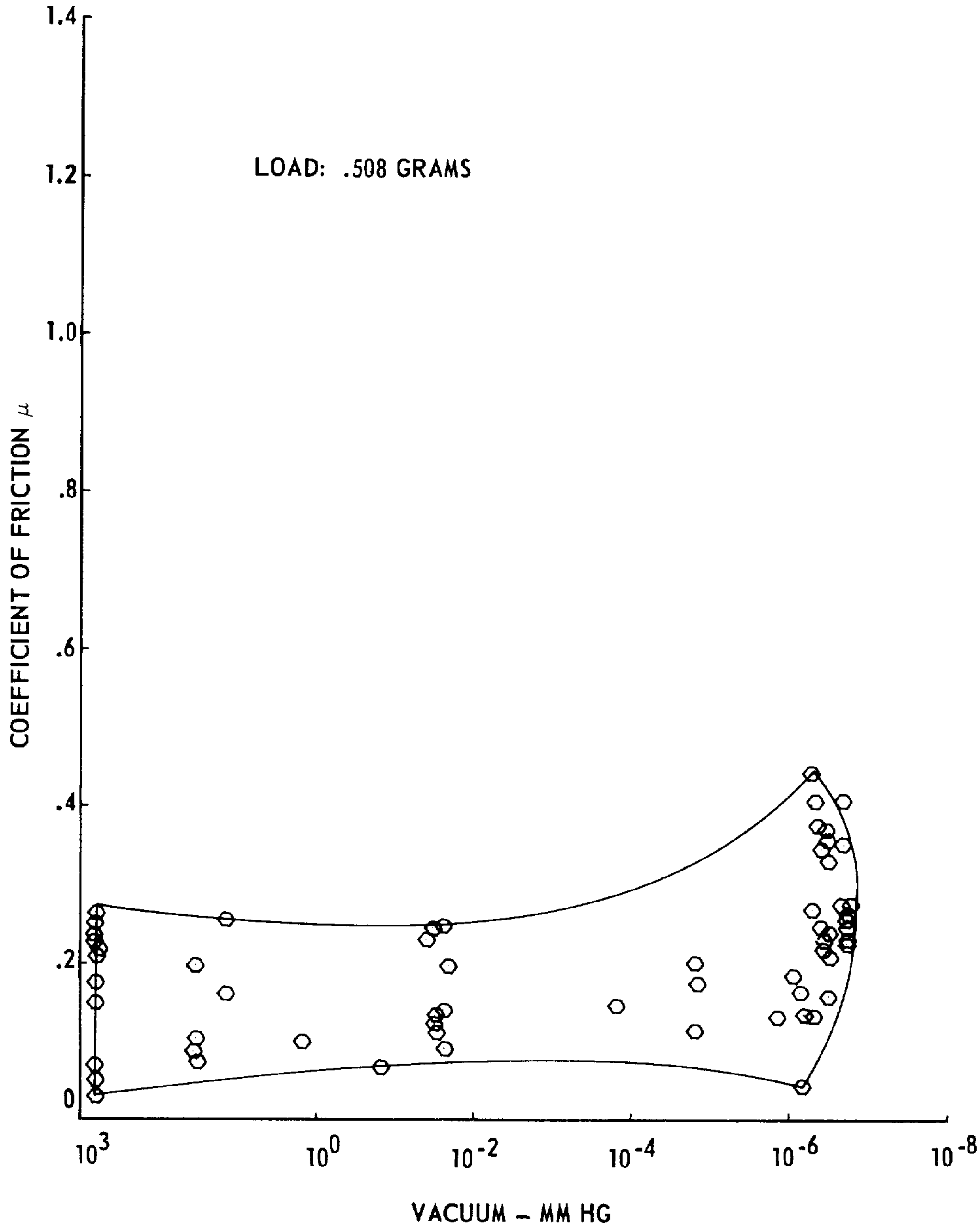


FIGURE 16. COEFFICIENT OF FRICTION VS. VACUUM

GLASS ON PYROCERAM

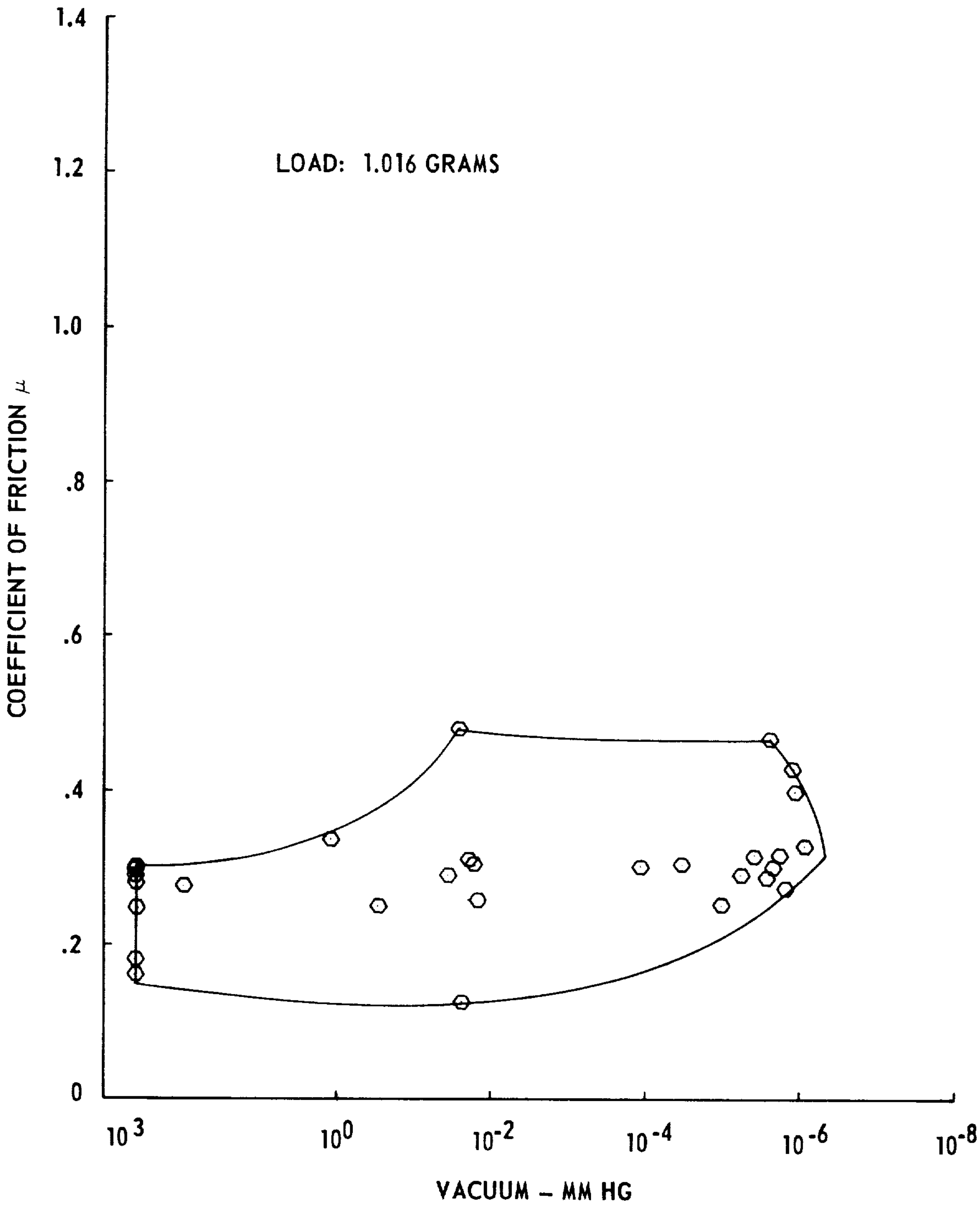


FIGURE 17. COEFFICIENT OF FRICTION VS. VACUUM

CIRCLE C ON NICKEL

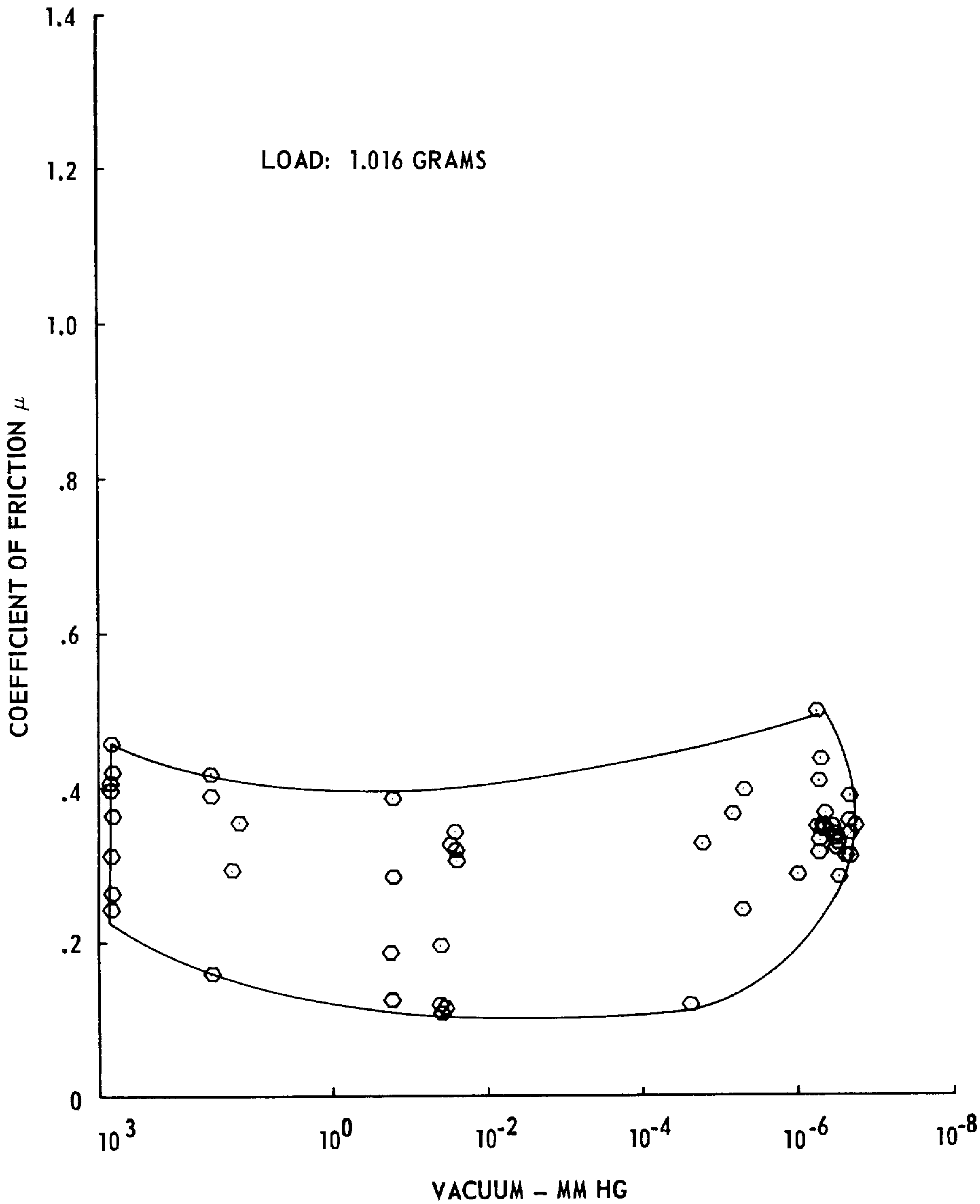


FIGURE 18. COEFFICIENT OF FRICTION VS. VACUUM
GLASS ON GLASS

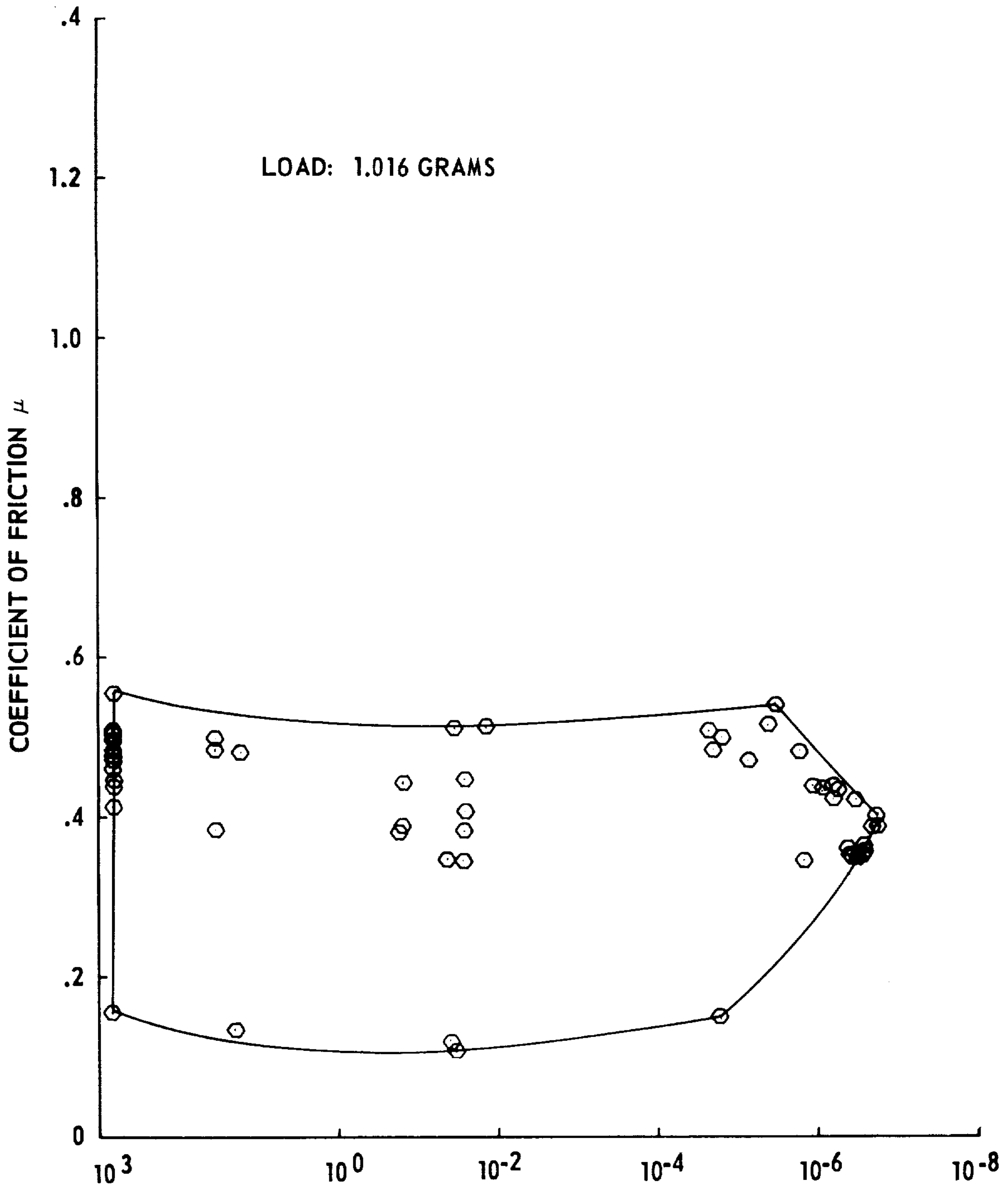


FIGURE 19. COEFFICIENT OF FRICTION VS. VACUUM

GLASS ON SAPPHIRE

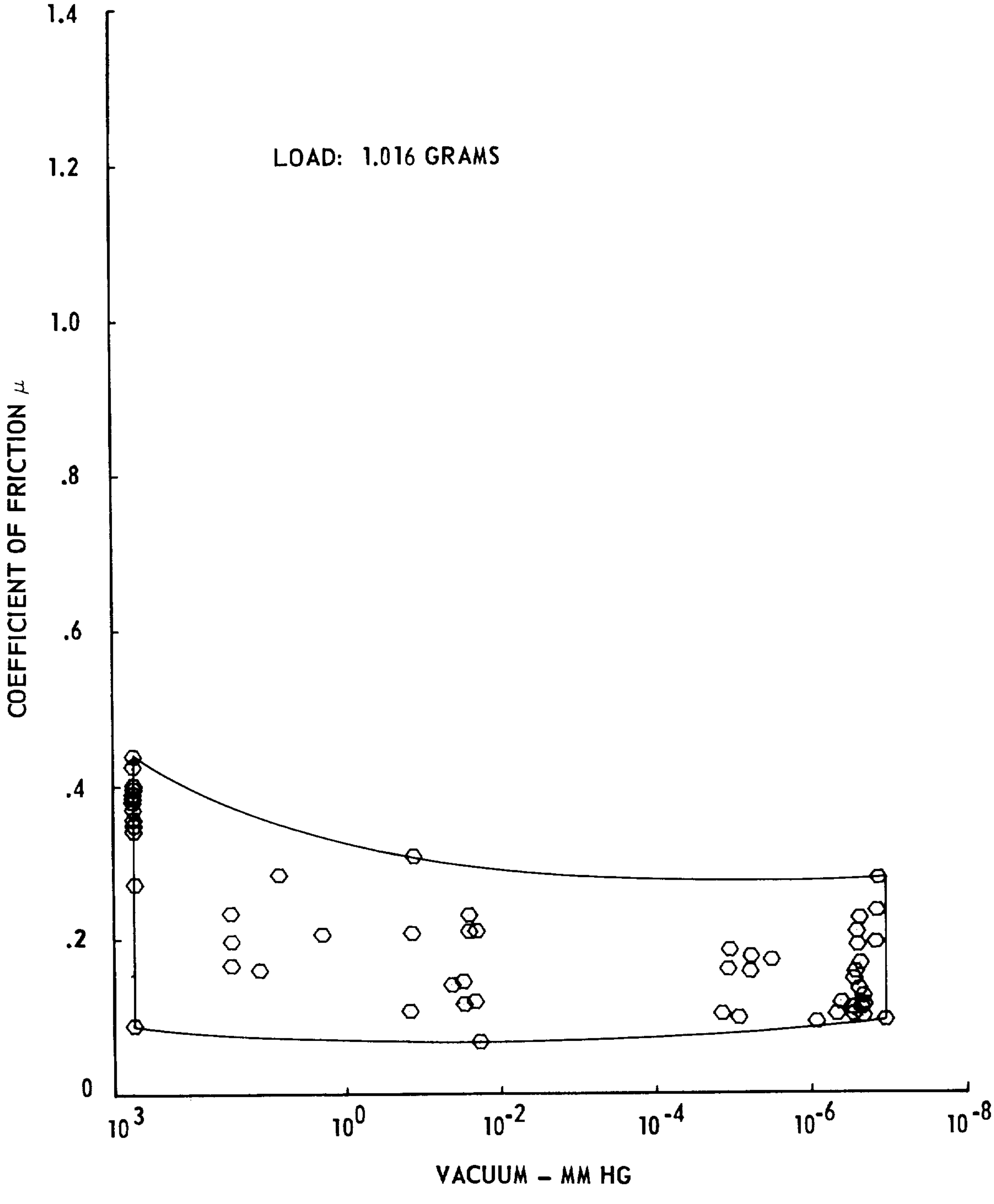


FIGURE 20. COEFFICIENT OF FRICTION VS. VACUUM
GLASS ON STELLITE

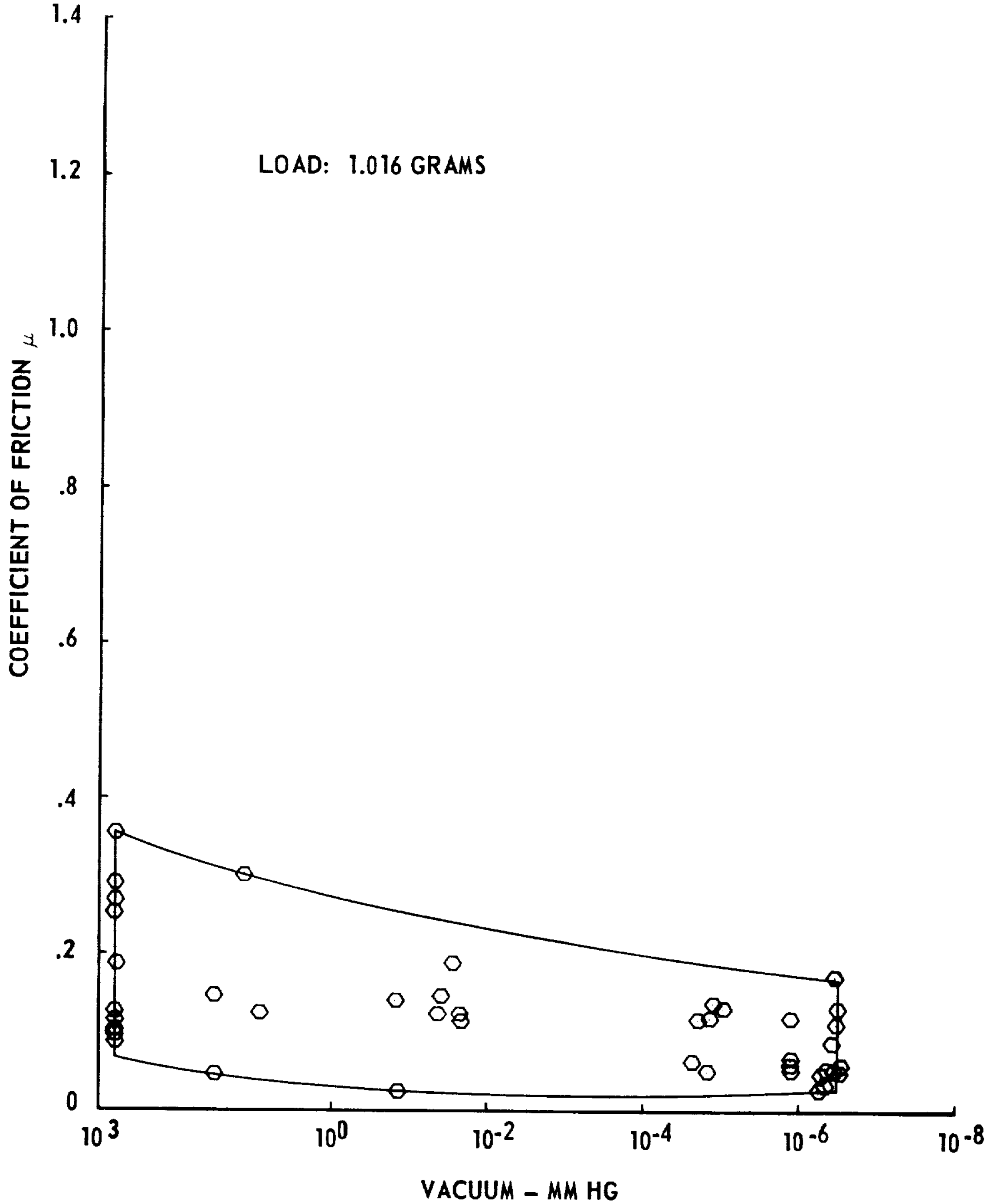


FIGURE 21. COEFFICIENT OF FRICTION VS. VACUUM
GLASS ON CIRCLE C

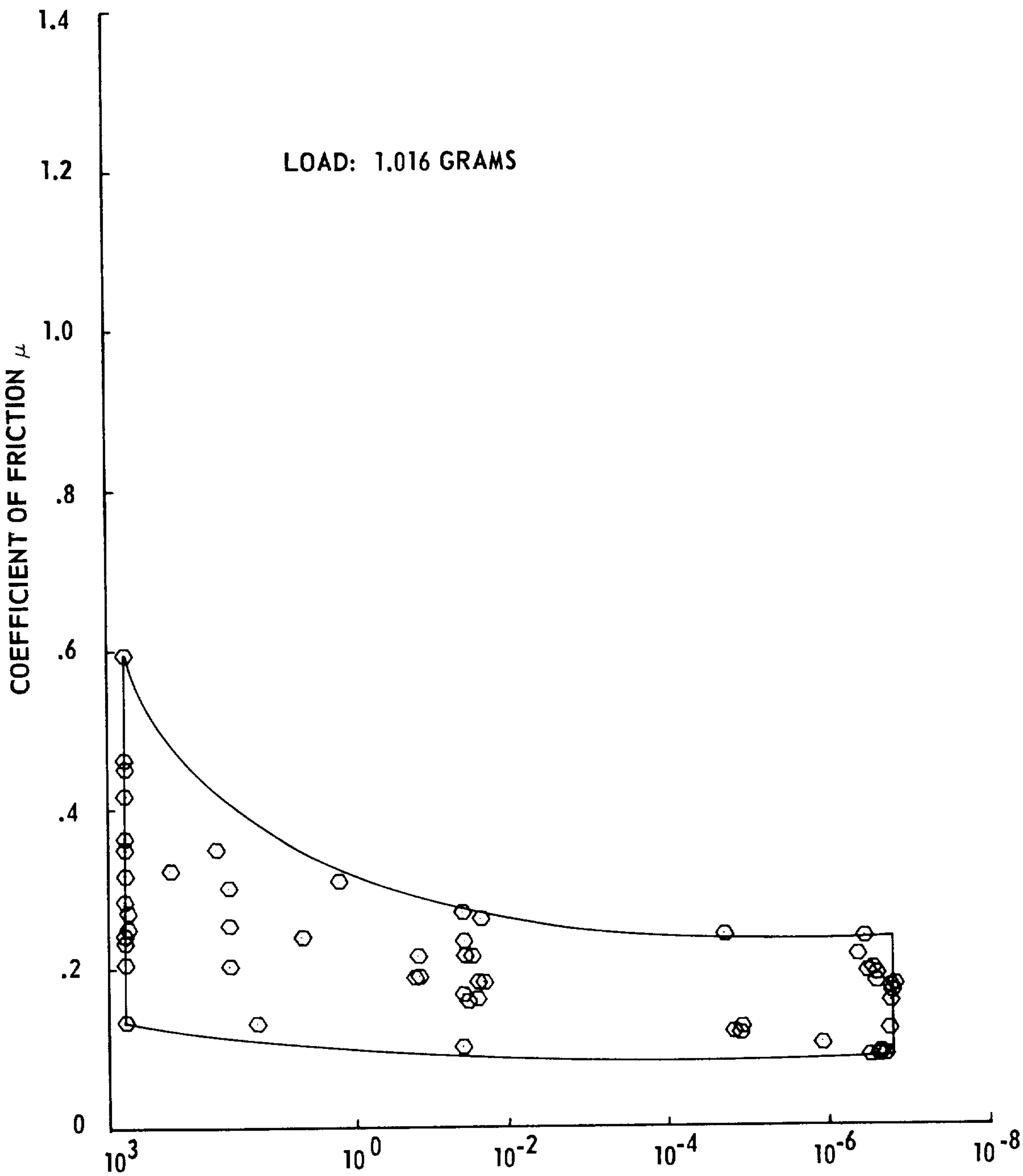


FIGURE 22. COEFFICIENT OF FRICTION VS. VACUUM
GLASS ON NICKEL

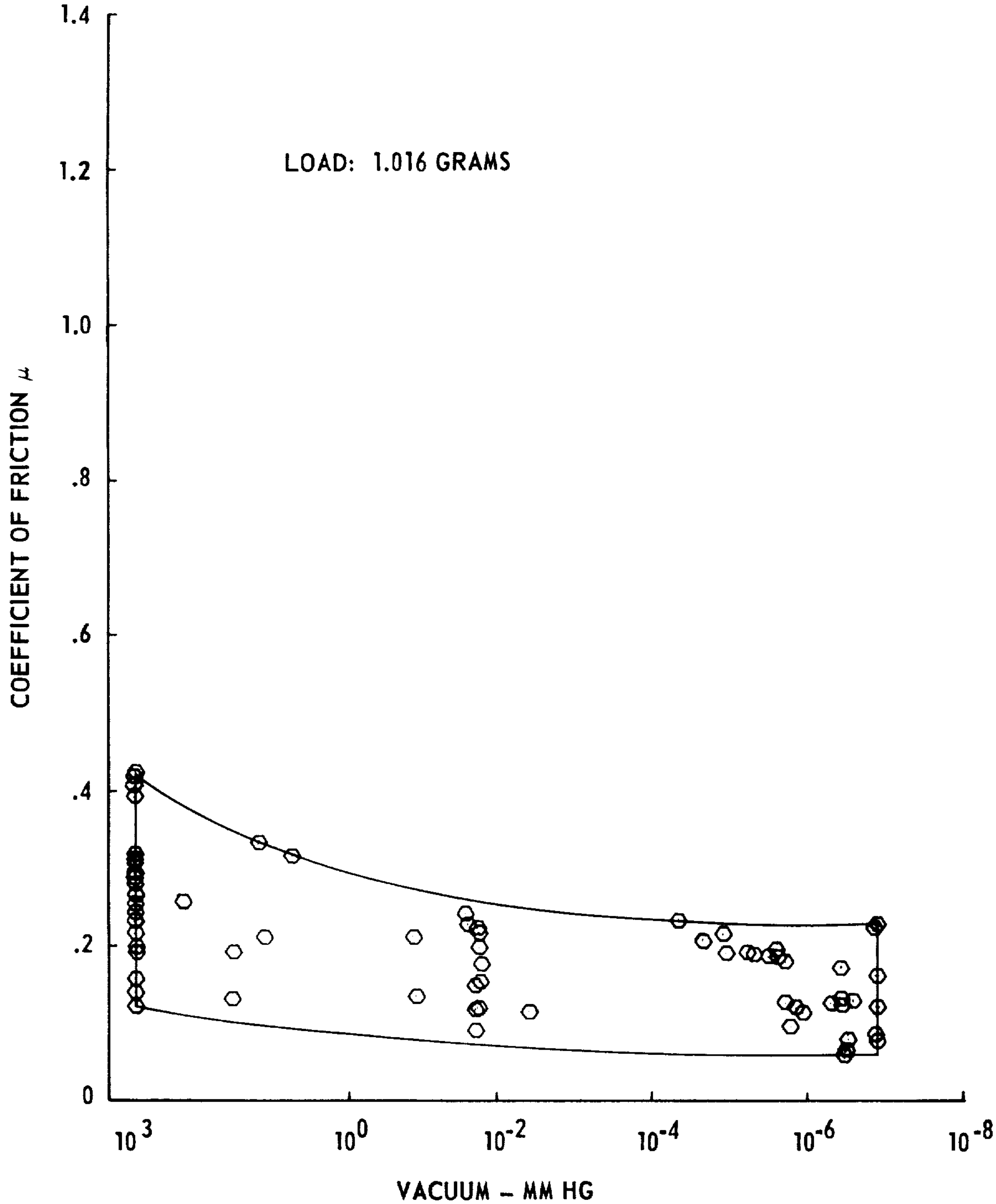


FIGURE 23. COEFFICIENT OF FRICTION VS. VACUUM
GLASS ON 440SS

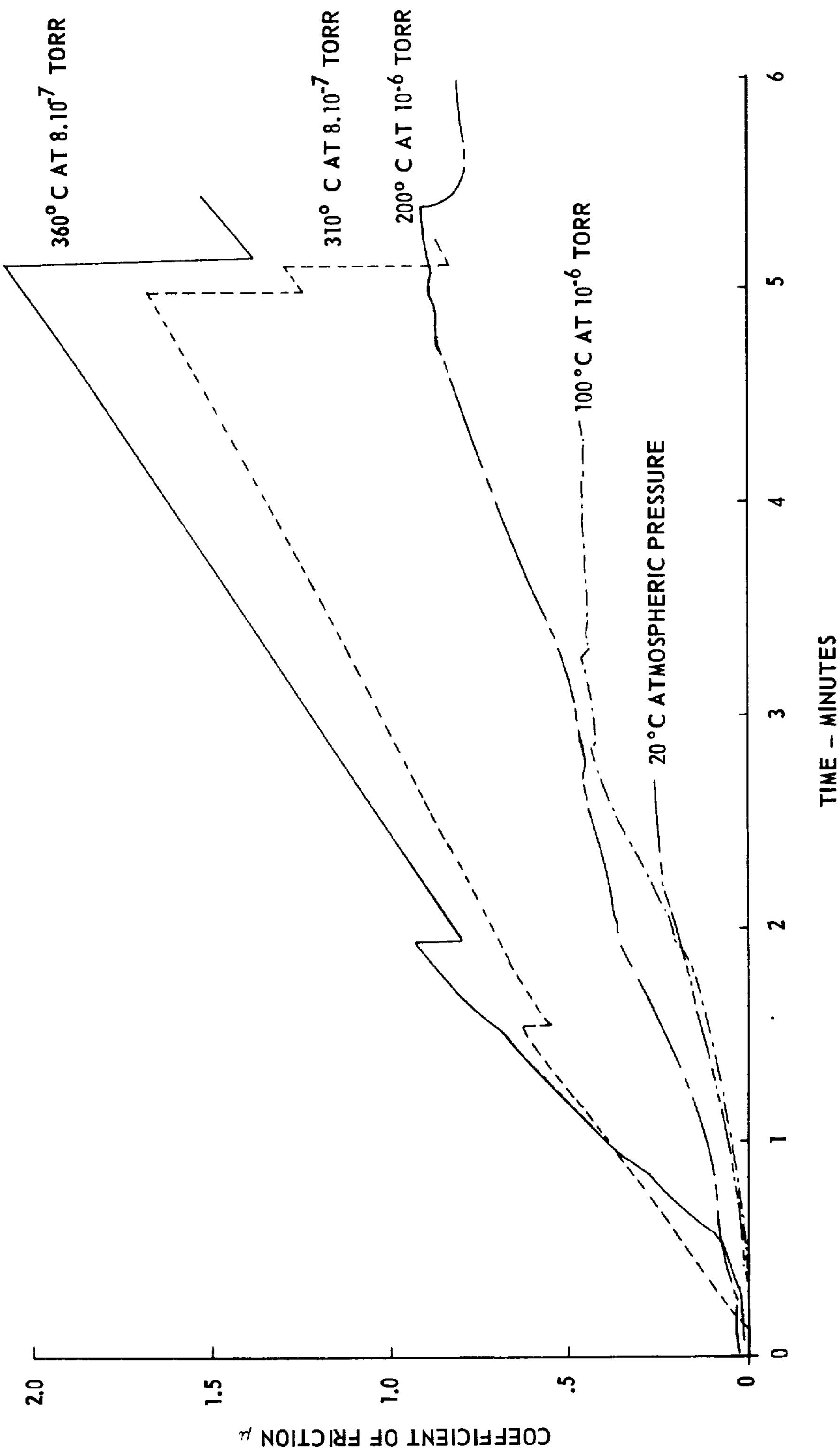


FIGURE 24. EXAMPLE OF FRICTION CHARACTERISTICS AT DIFFERENT TEMPERATURES AND PRESSURES: BRASS ON PHOSPHOR BRONZE

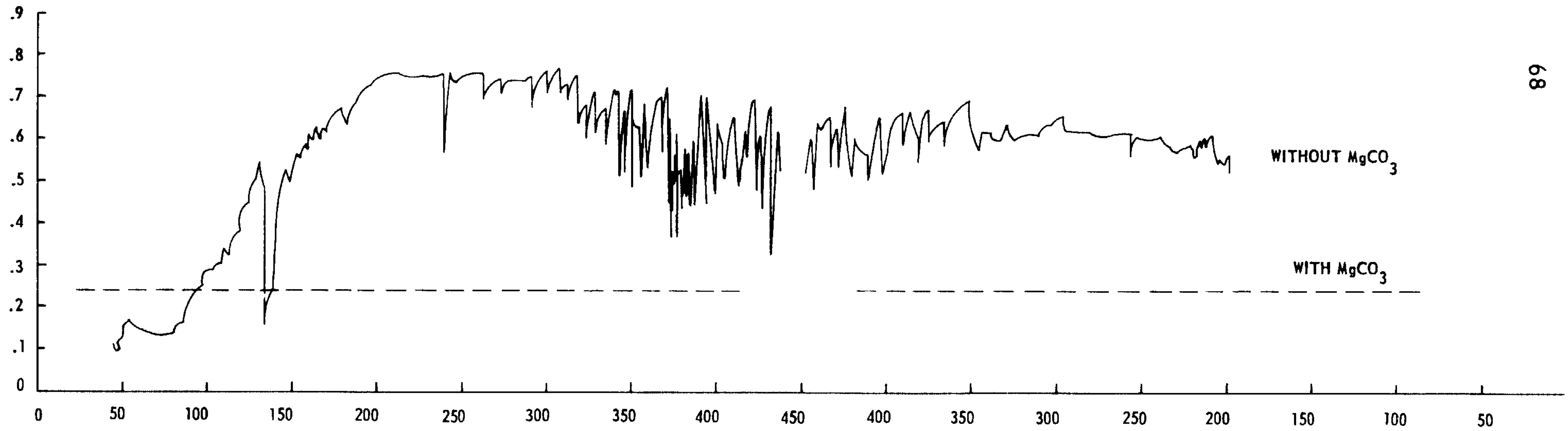


FIGURE 25. FRICTION CHARACTERISTICS WITH AND WITHOUT APPLICATION OF $MgCO_3$
(STELLITE ON STELLITE)

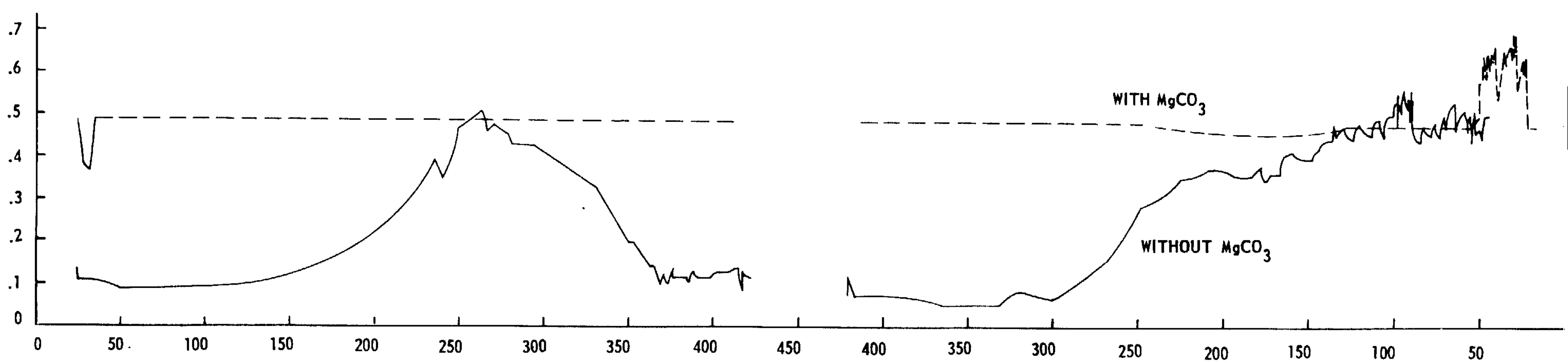


FIGURE 26. FRICTION CHARACTERISTICS WITH AND WITHOUT APPLICATION OF $MgCO_3$
(STELLITE ON GLASS)

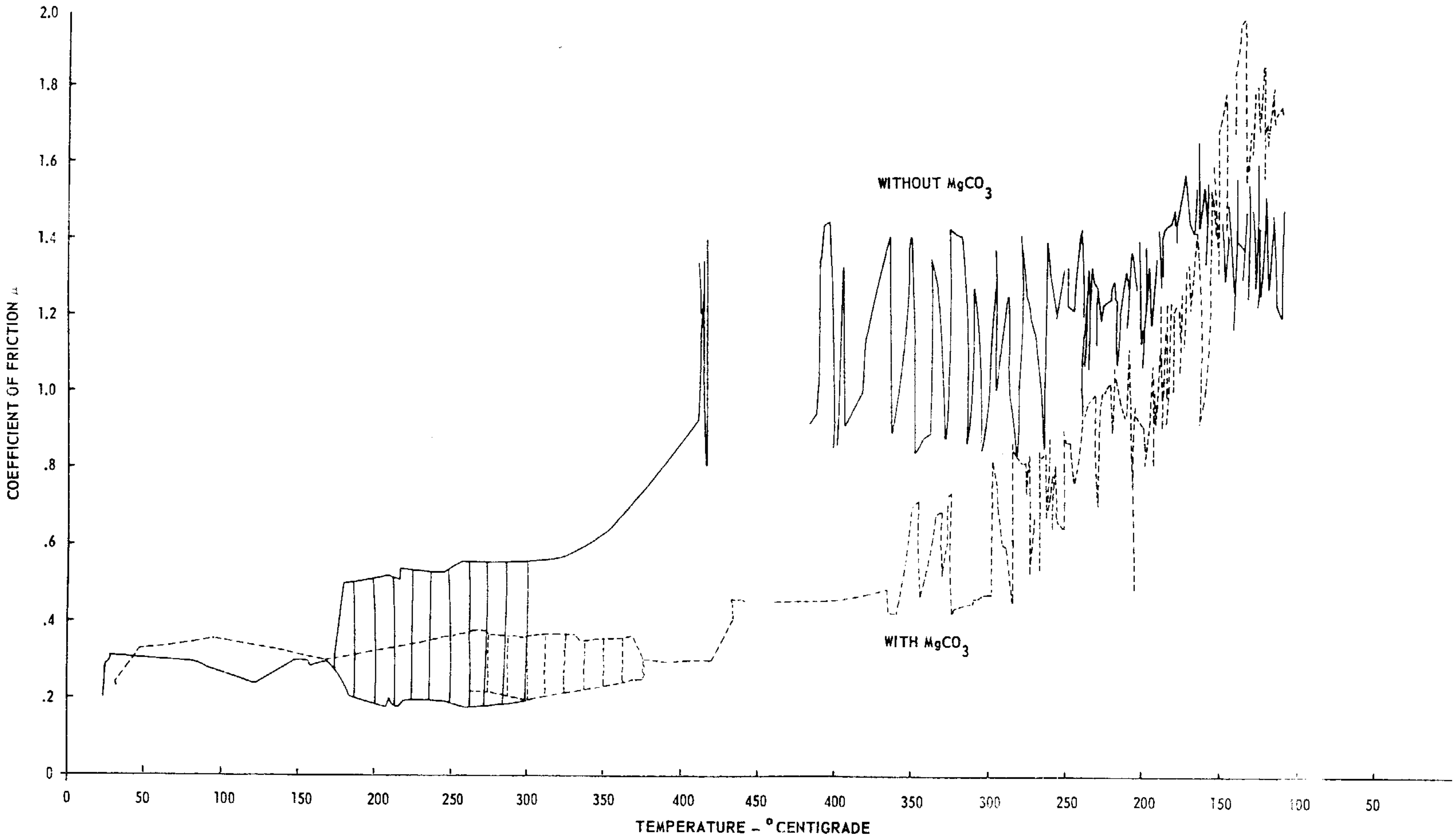


FIGURE 27. FRICTION CHARACTERISTICS WITH AND WITHOUT APPLICATION OF $MgCO_3$ (PHOSPHOR-BRONZE ON PHOSPHOR-BRONZE)

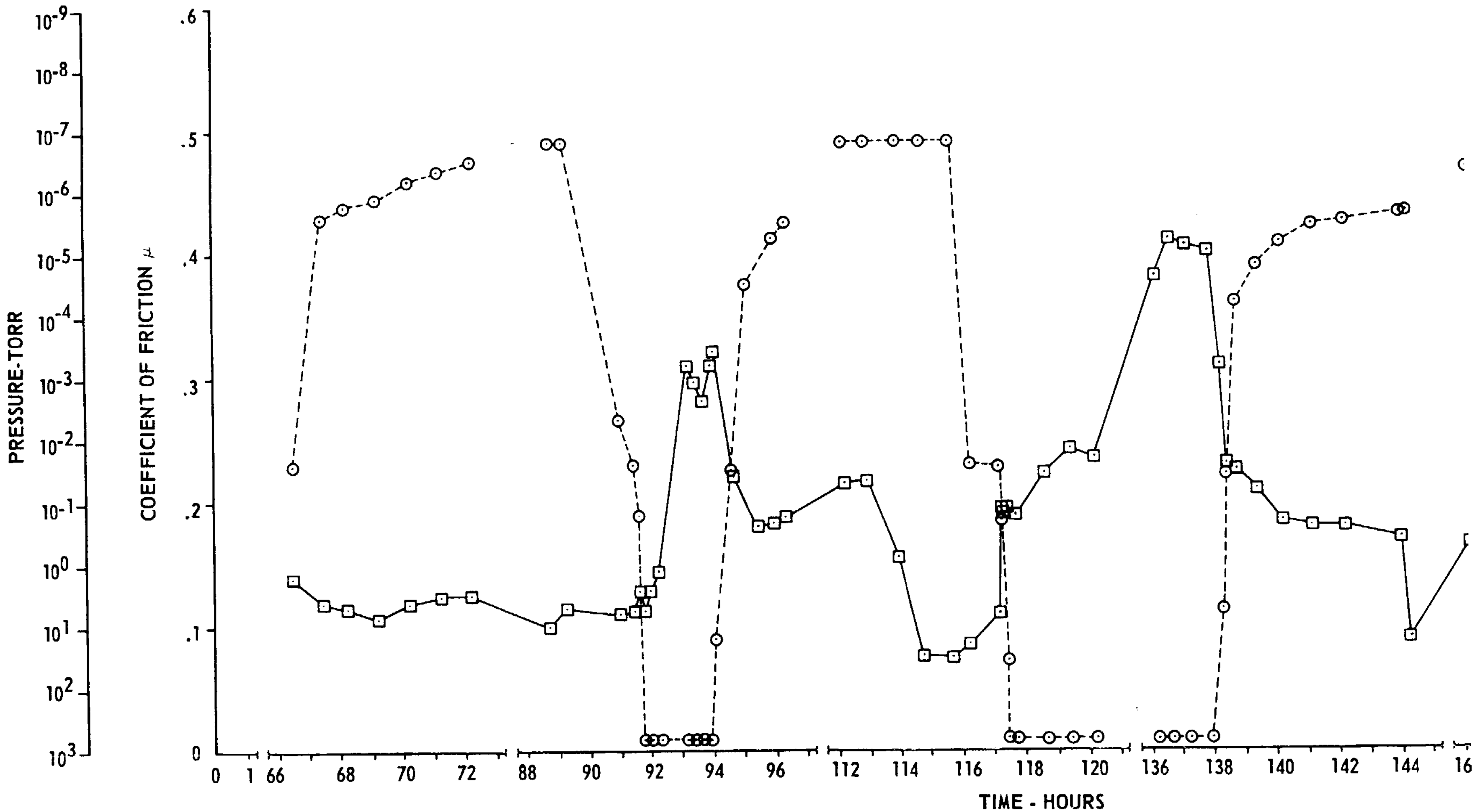
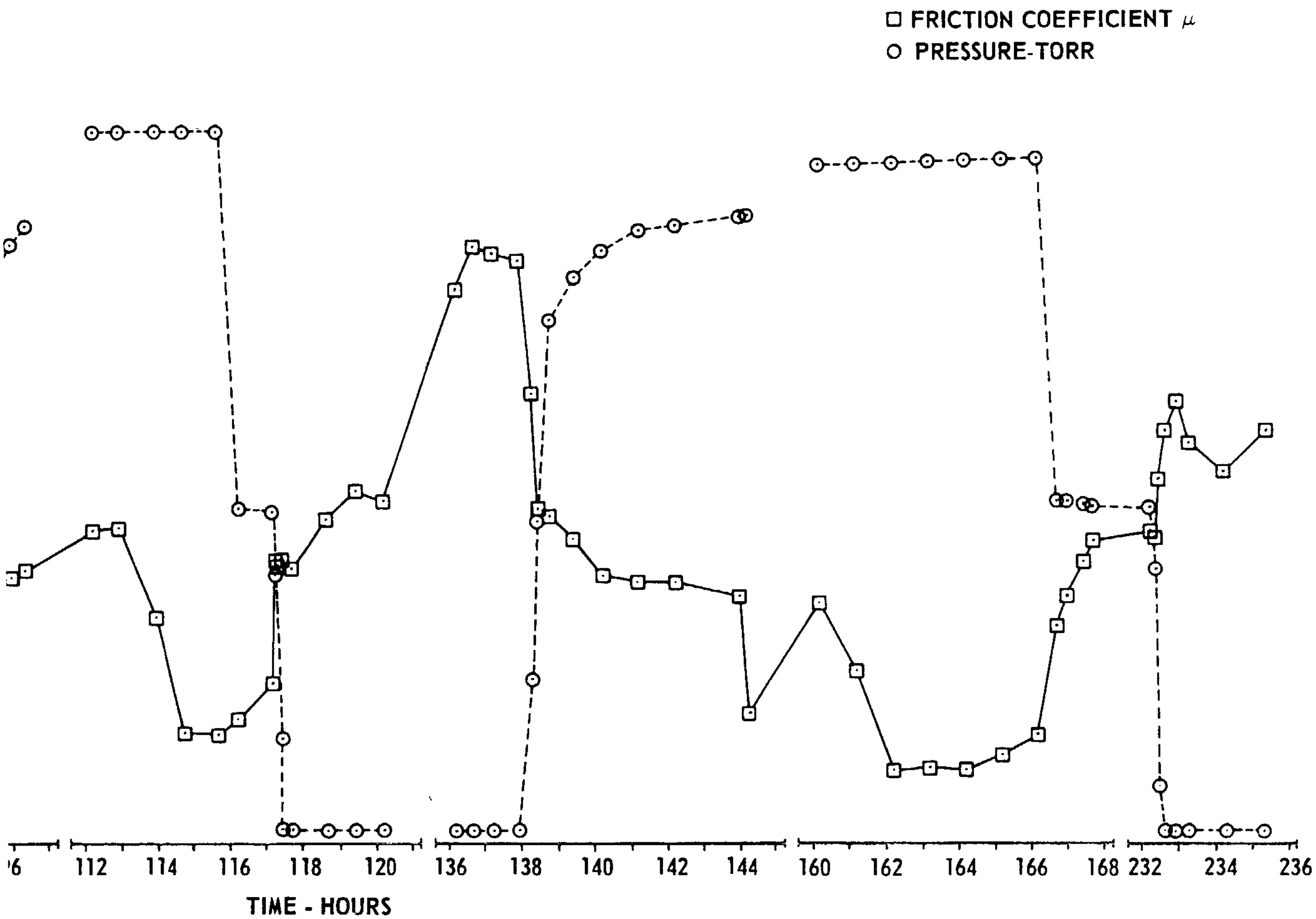


FIGURE 28. GLASS ON 440-SS. FRICTIONAL BEHAVIOR UNDER SUBSEQUENT PRESSURE VARIATIC



ı 440-SS. FRICTIONAL BEHAVIOR UNDER SUBSEQUENT PRESSURE VARIATIONS

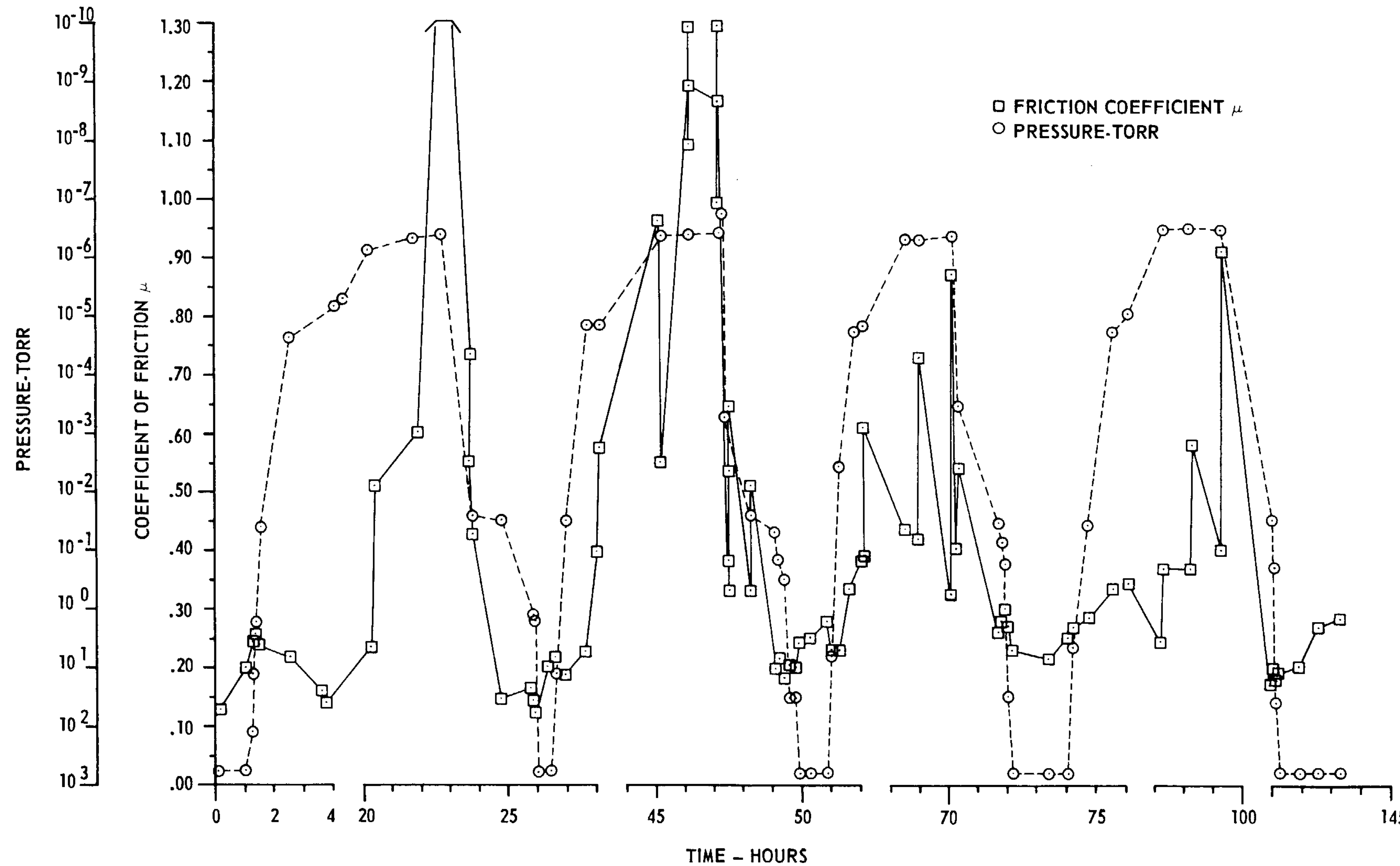


FIGURE 29. HASTELLOY ON NICKEL. FRICTIONAL BEHAVIOR UNDER SUBSEQUENT PRESSURE VARIATIONS

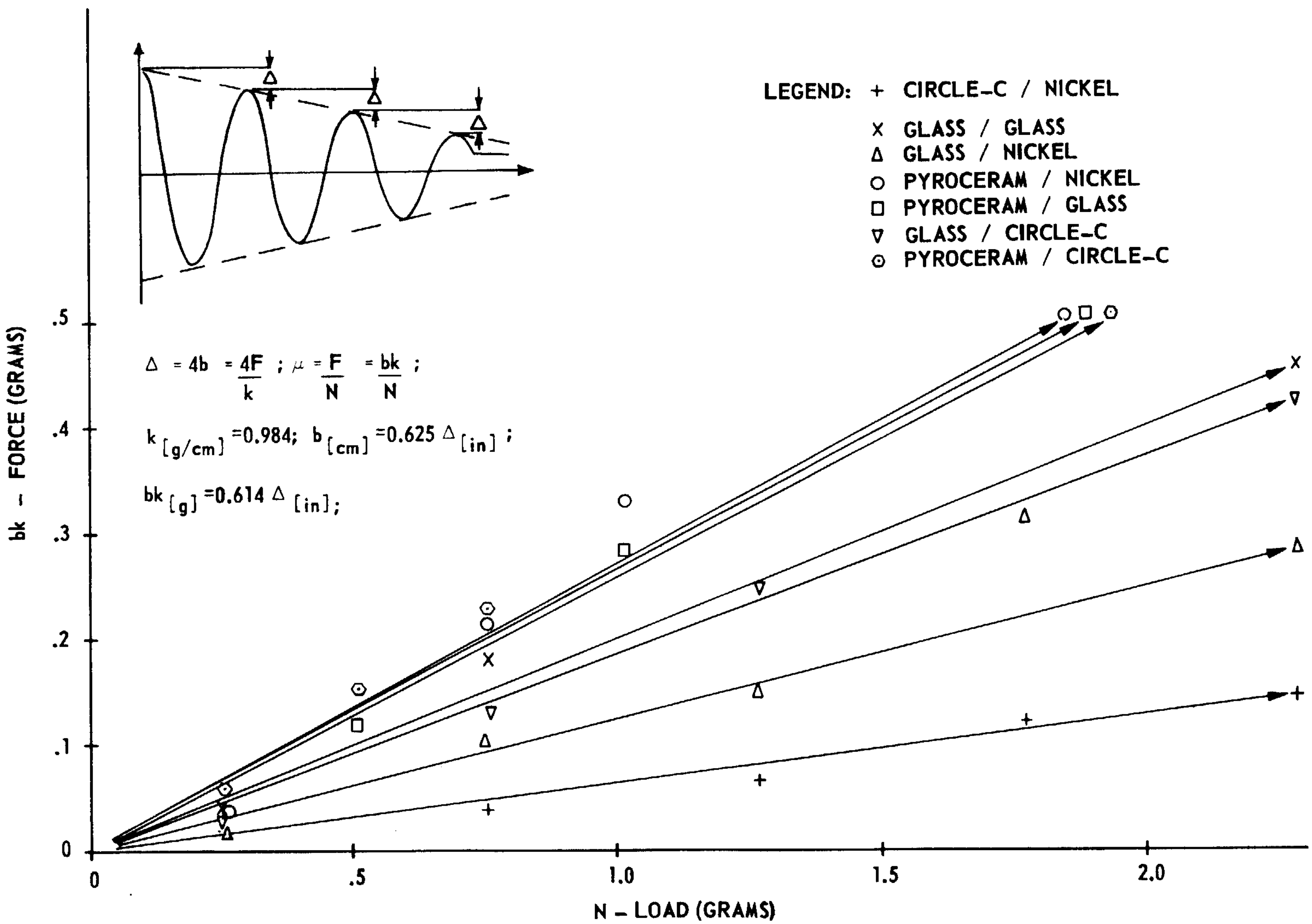


FIGURE 30. FRICTION OF VARIOUS MATERIAL COMBINATIONS AND DIFFERENT LOADS AT ATMOSPHERIC PRESSURE

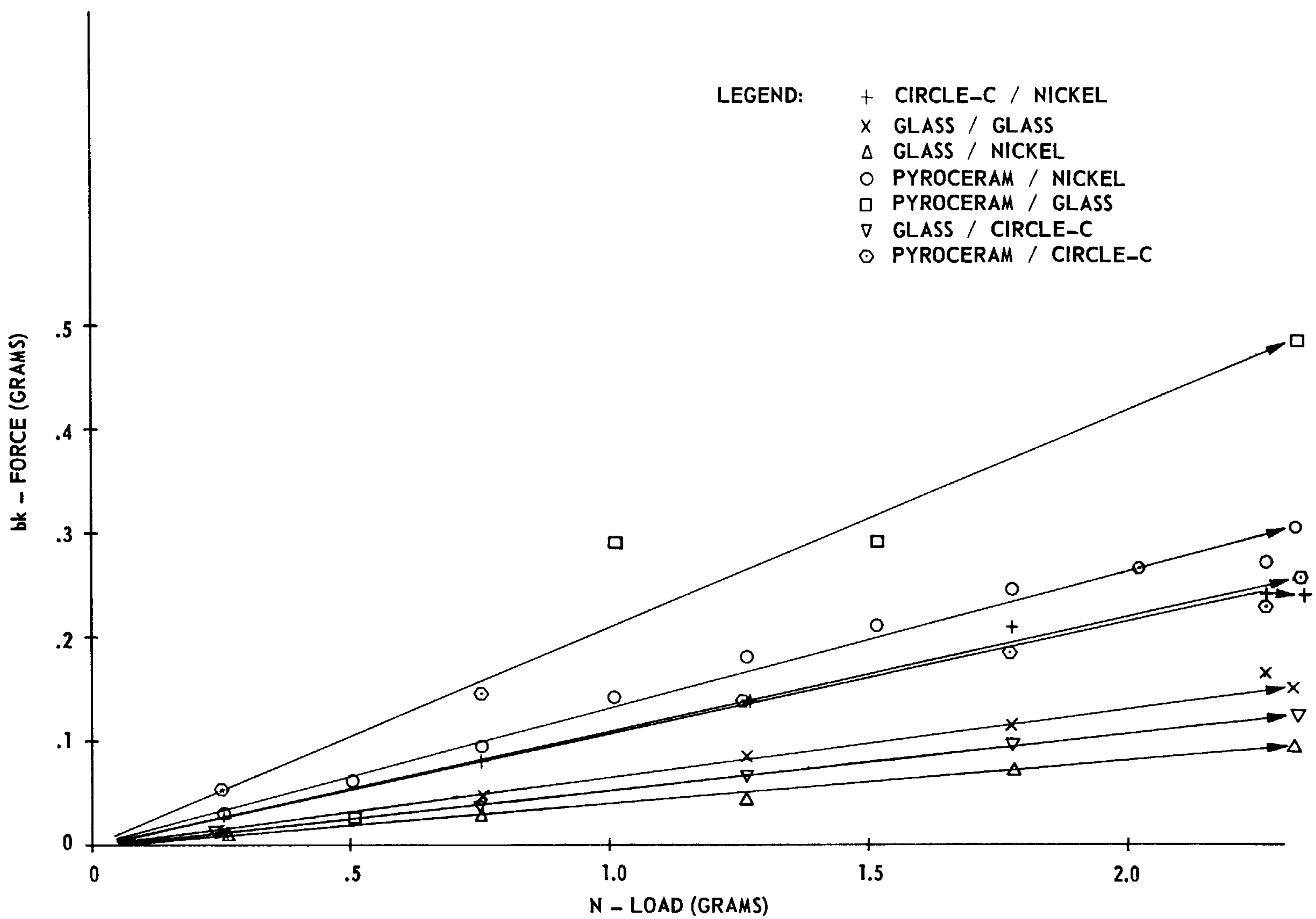


FIGURE 31. FRICTION OF MATERIAL COMBINATIONS OF FIGURE 30 AT HIGH VACUUM (10^{-7} TORR)

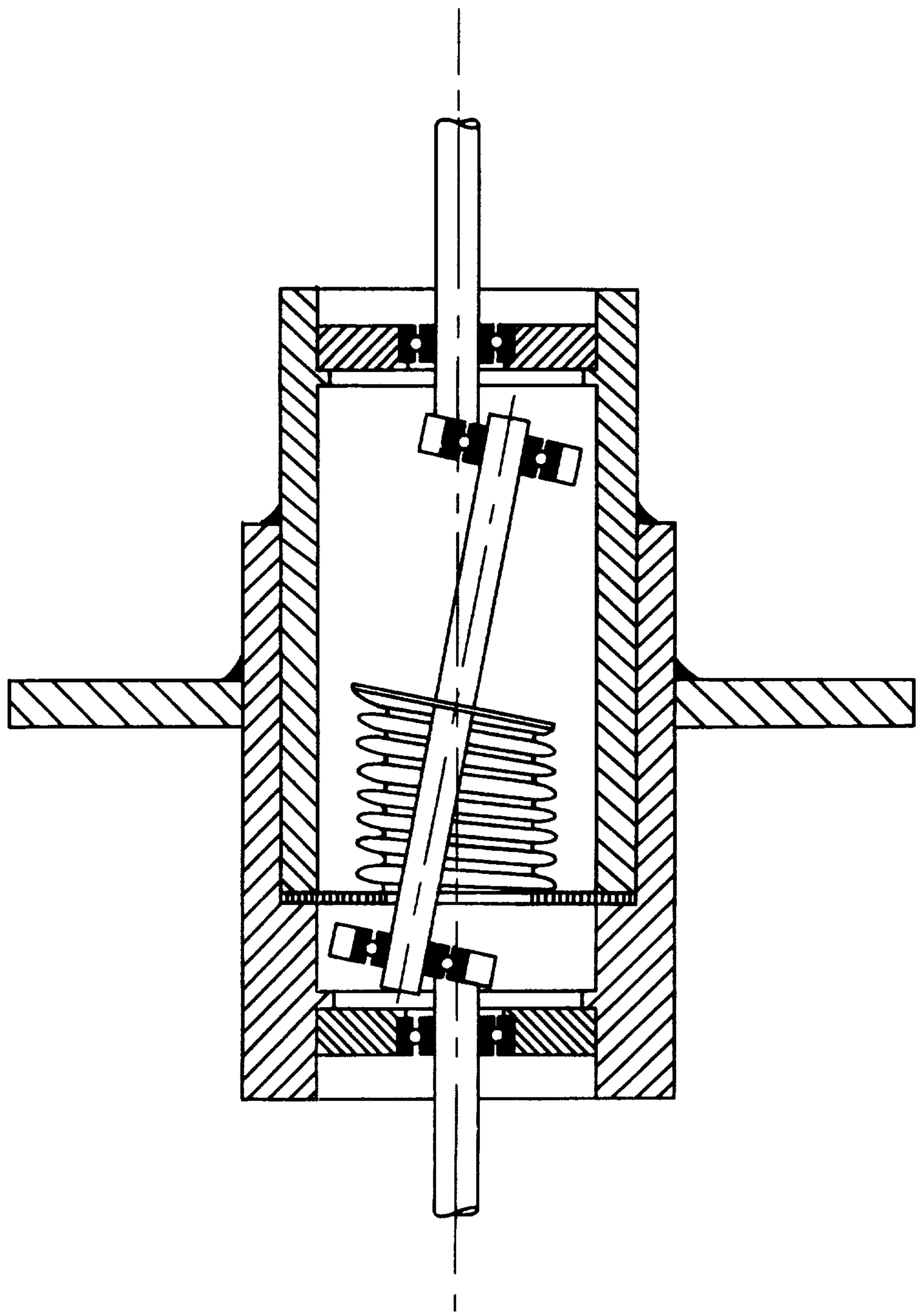


FIGURE 32. DESIGN PRINCIPLE OF TORQUE TRANSMITTER

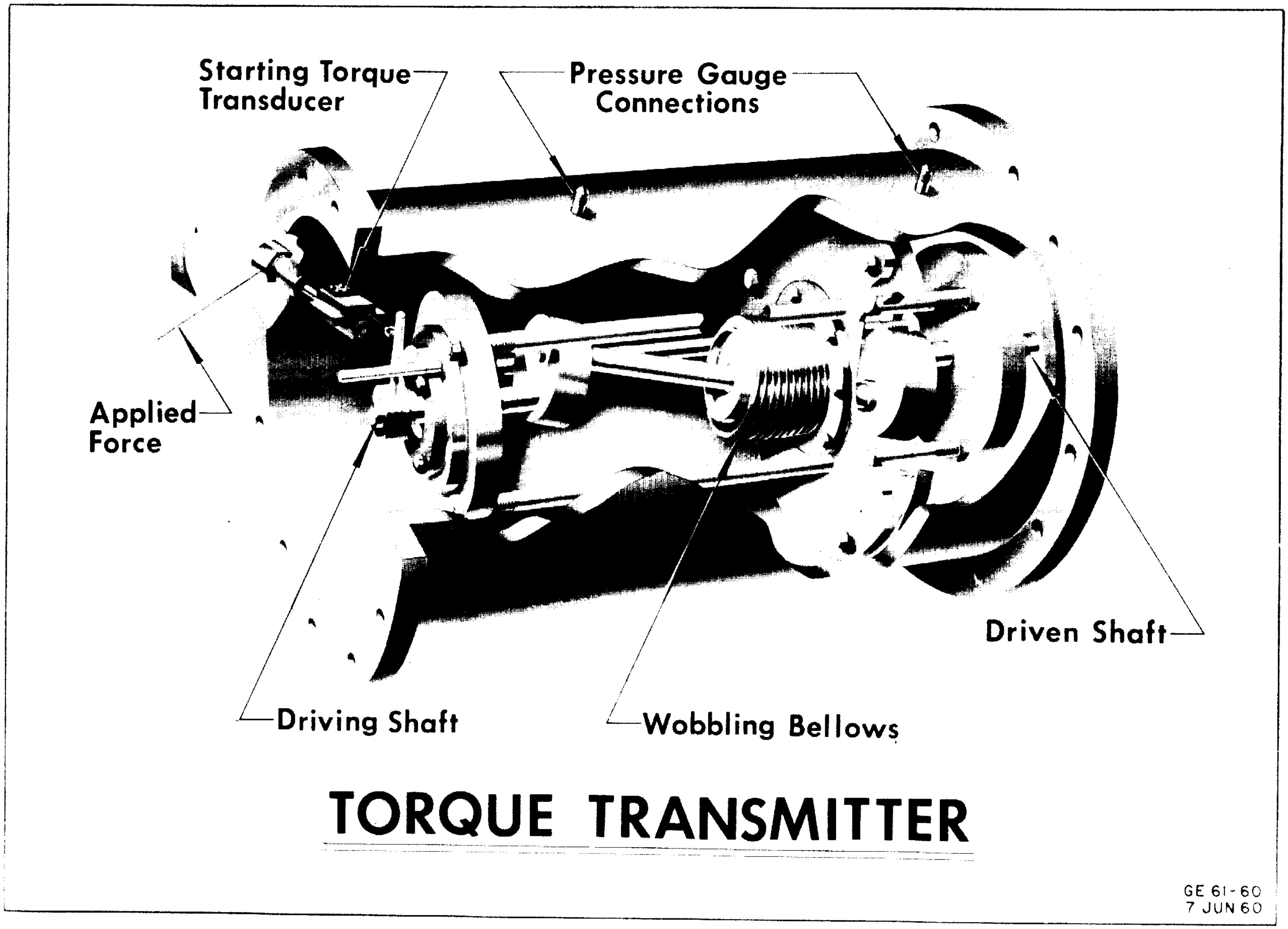


FIGURE 33. TORQUE TRANSMITTER

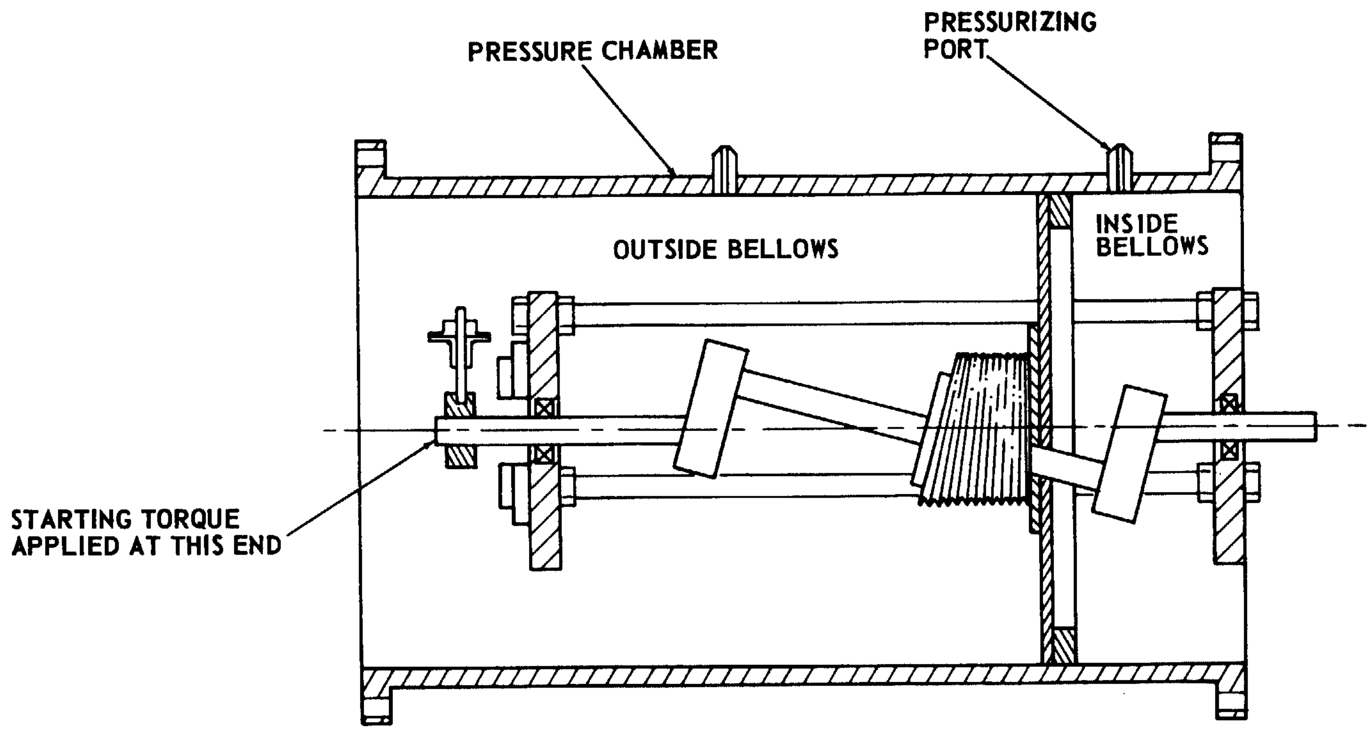


FIGURE 34. SCHEMATIC OF TEST SET-UP FOR MEASURING STARTING TORQUE WITH A PRESSURE DIFFERENTIAL ON THE BELLOWS OF THE TORQUE TRANSMITTER

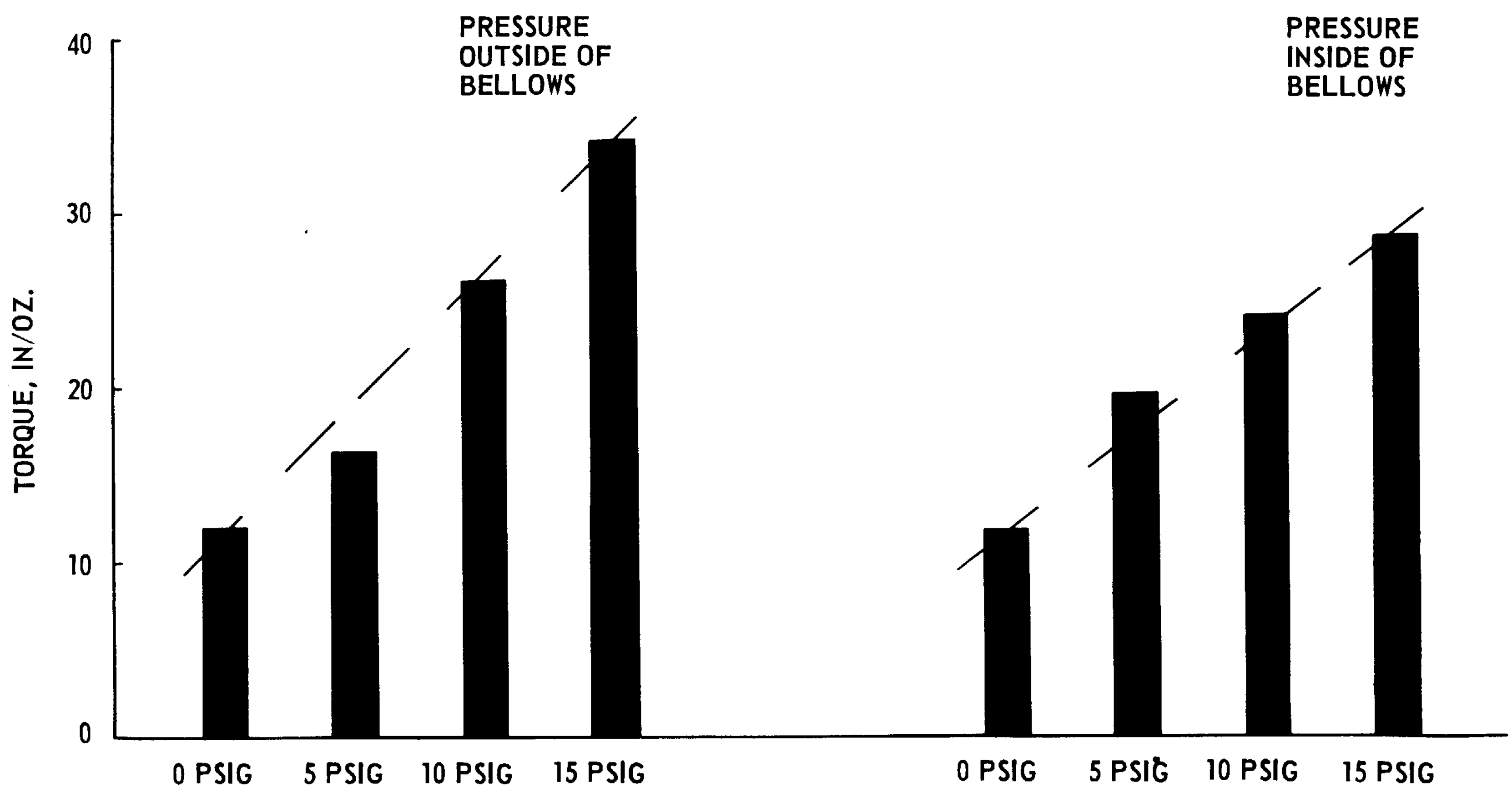


FIGURE 35 TORQUE TRANSMITTER STARTING TORQUE DATA

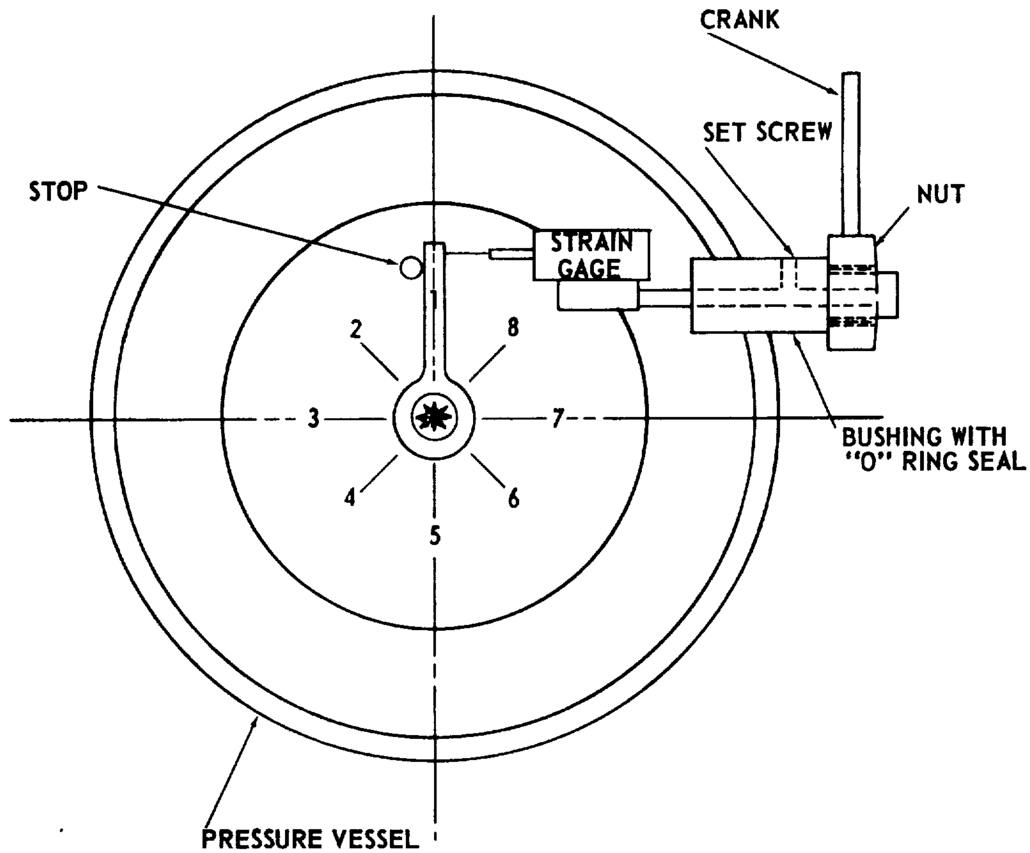


FIGURE 36. SCHEMATIC OF TEST SET-UP FOR MEASURING STARTING TORQUE WITH A PRESSURE DIFFERENTIAL ON THE BELLOWS OF THE TORQUE TRANSMITTER

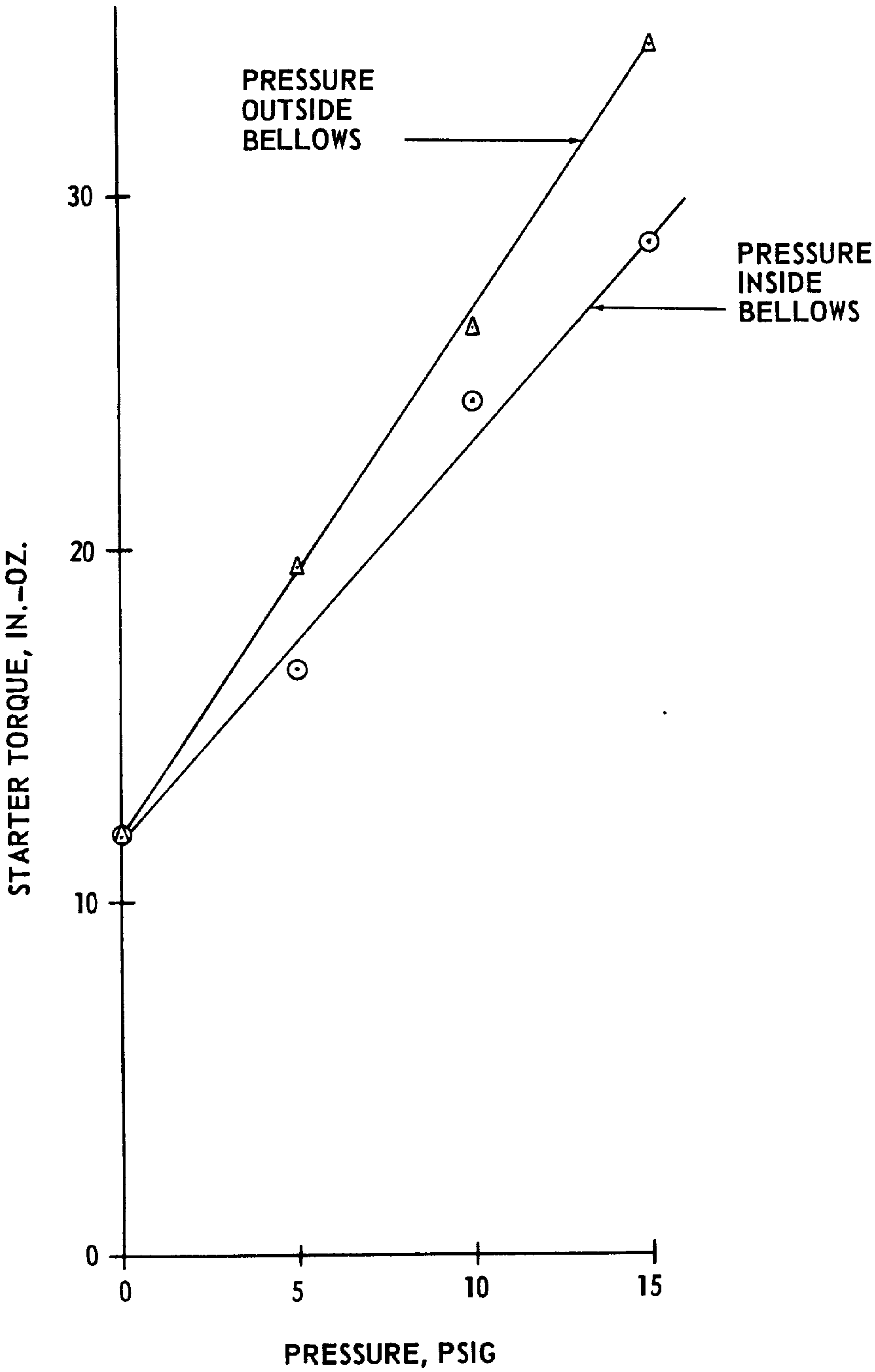


FIGURE 37 TORQUE TRANSMITTER STARTING TORQUE DA'

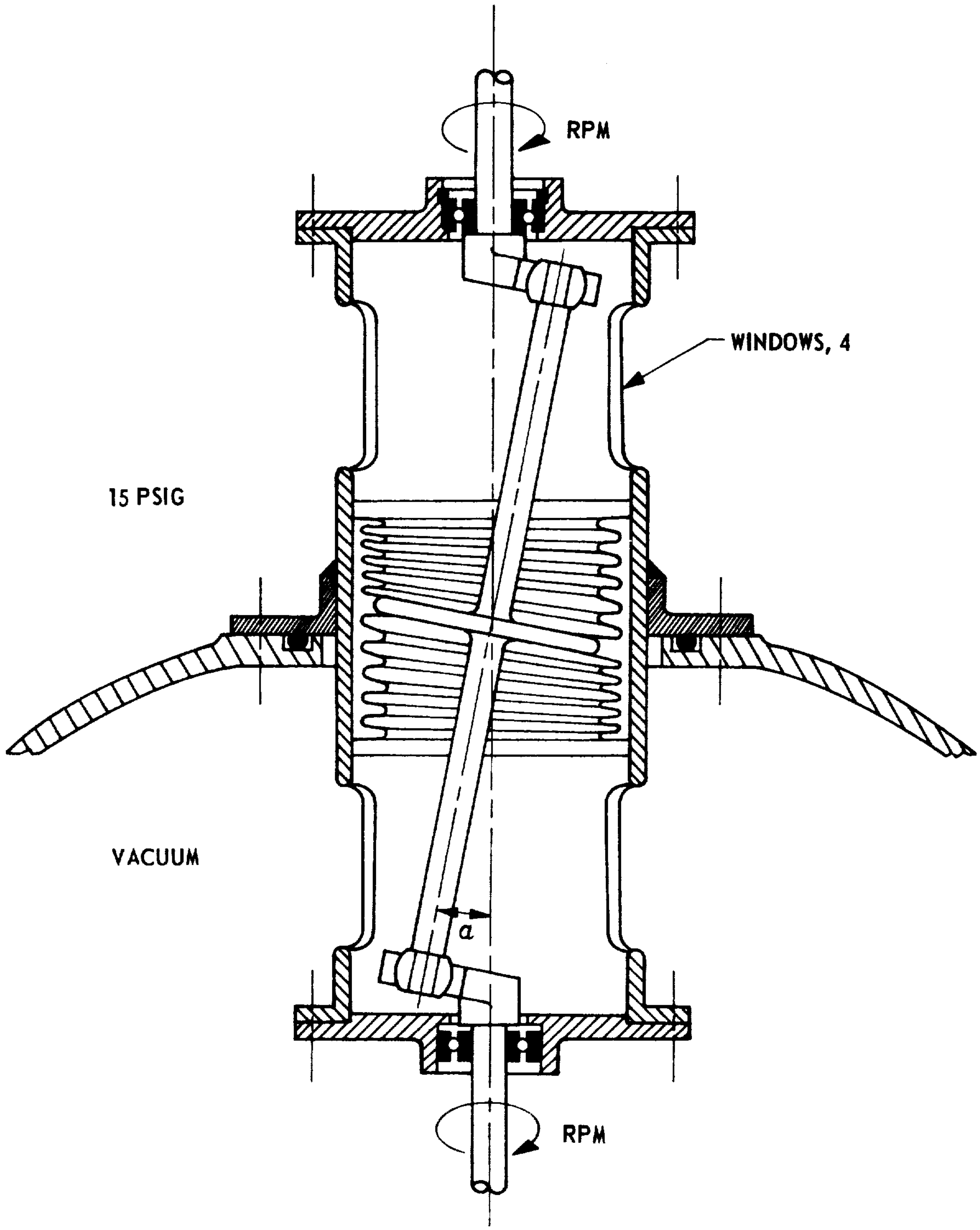


FIGURE 38. HERMETICALLY SEALED MECHANICAL TORQUE TRANSMITTER

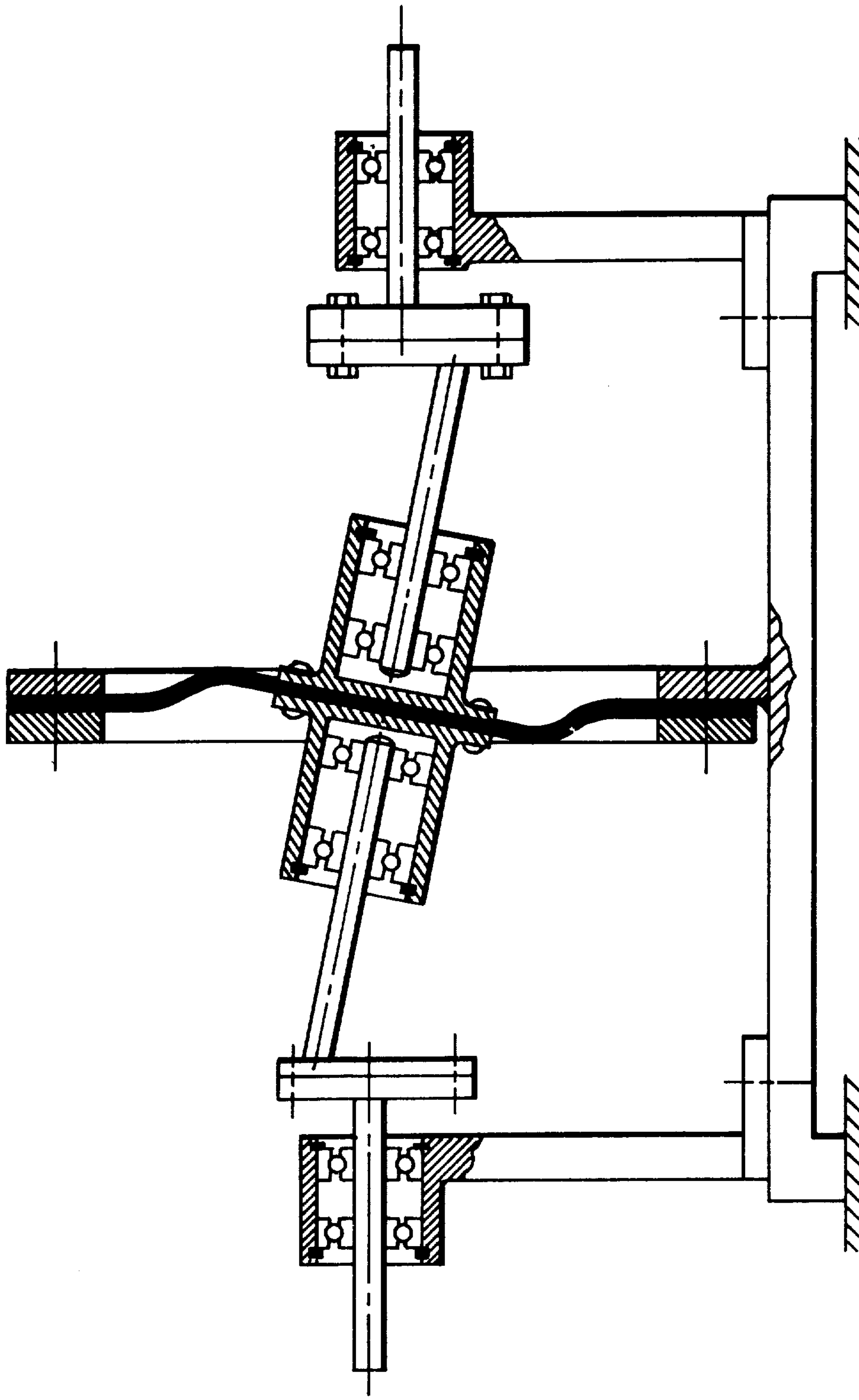


FIGURE 39. TORQUE TRANSMITTER WITH MEMBRANE SEAL

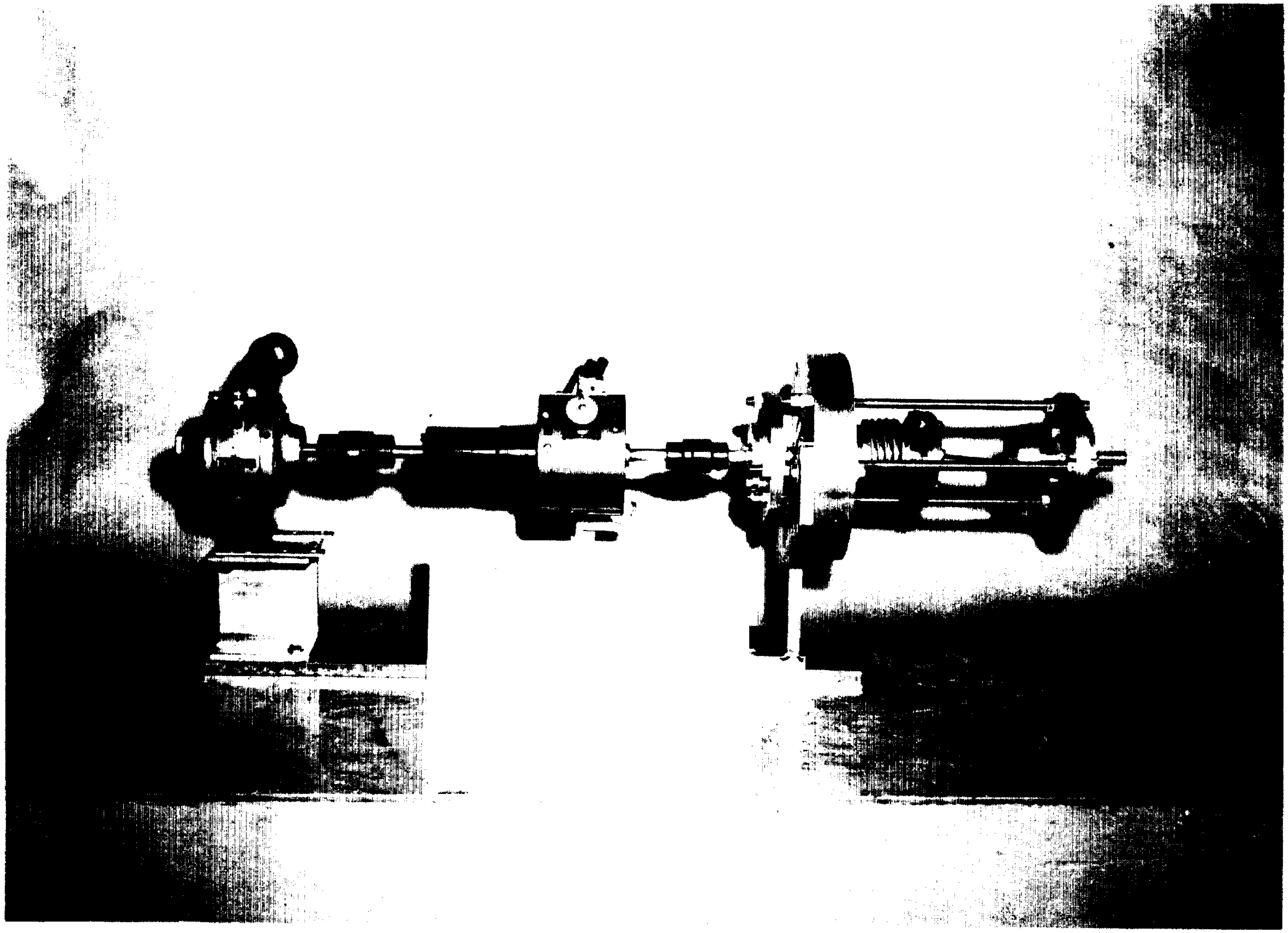


FIGURE 40. TORQUE TRANSMITTER TEST SET-UP

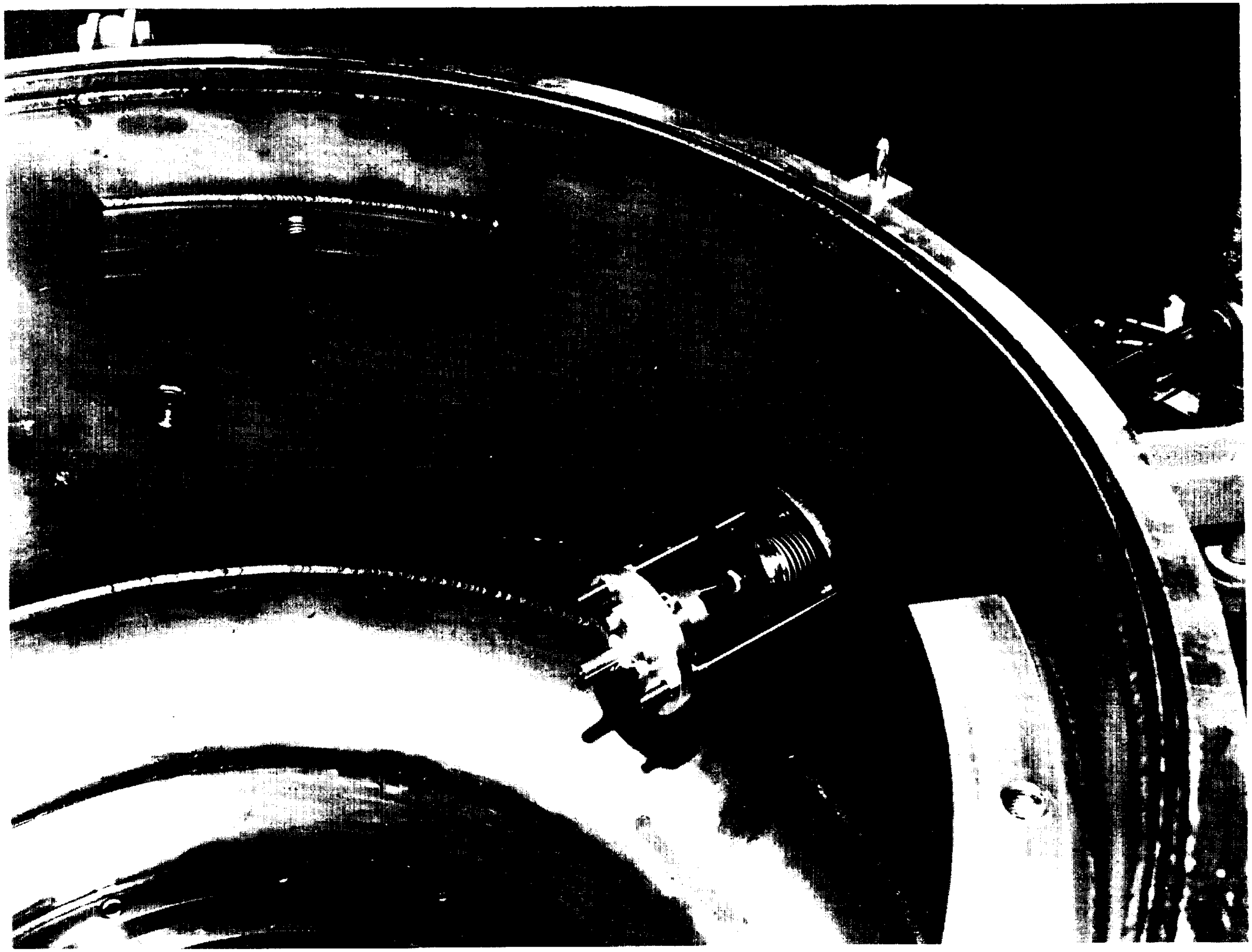


FIGURE 41. TORQUE TRANSMITTER MOUNTED IN VACUUM CHAMBER

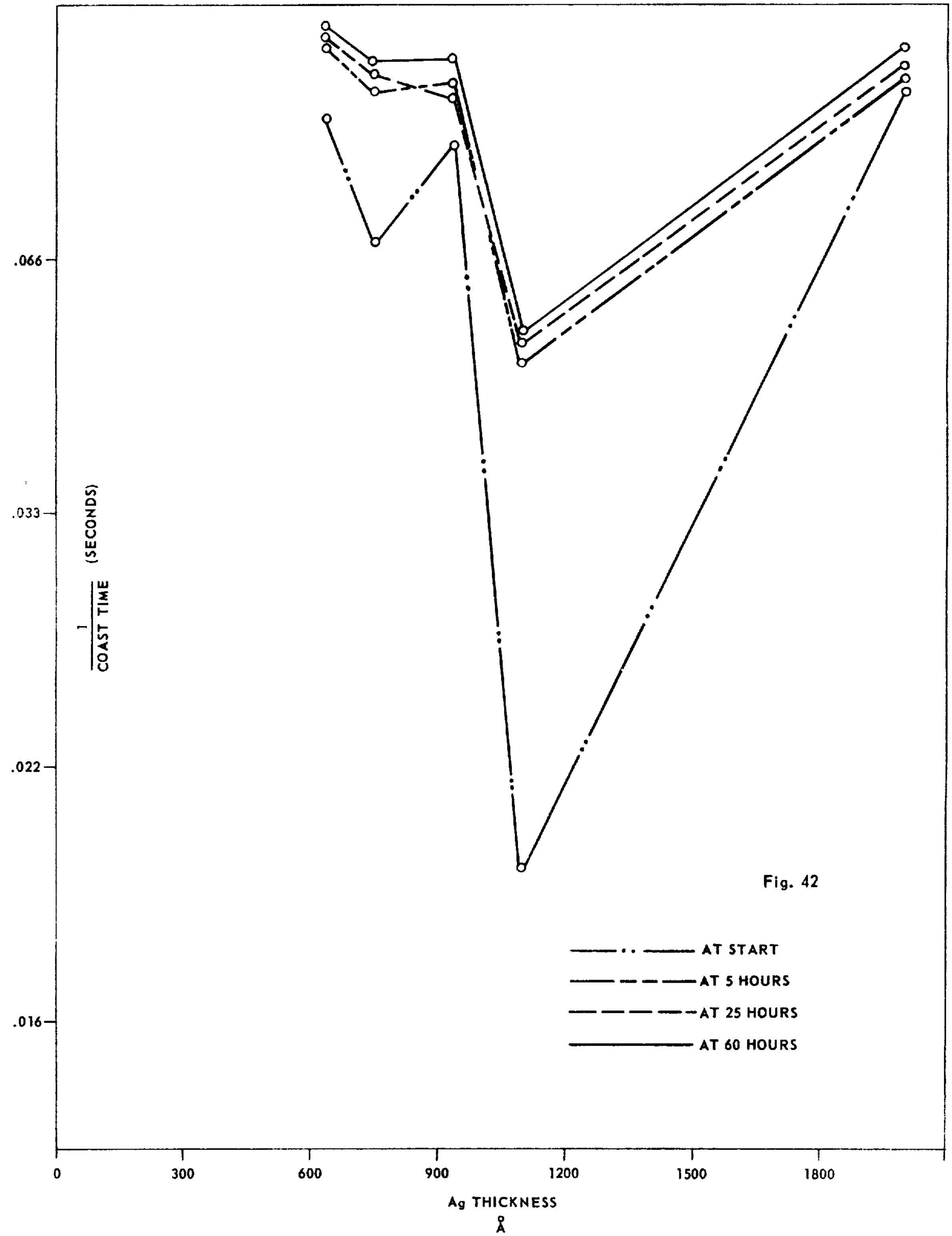
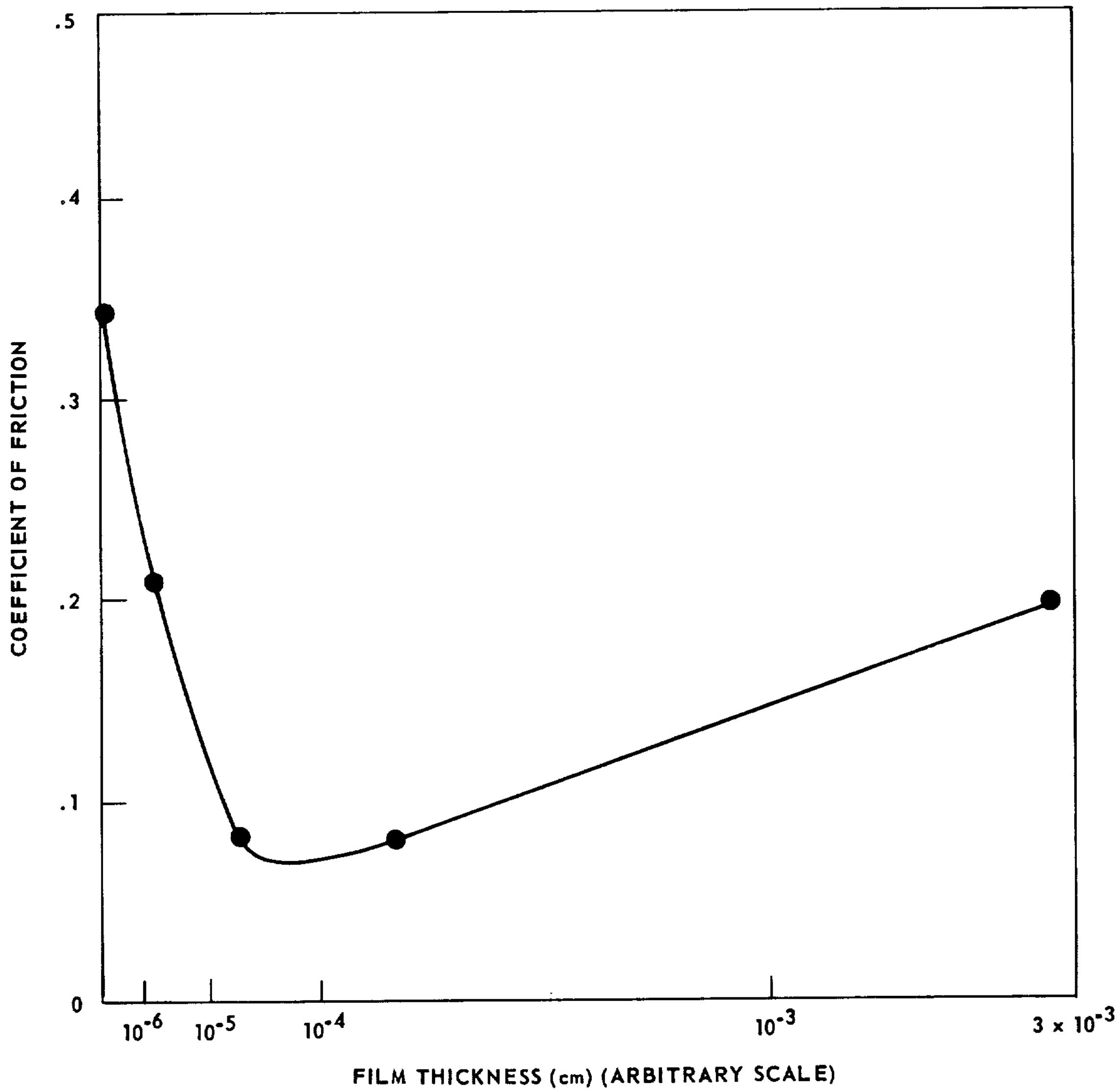

.066
.033
.022
.016
1 / COAST TIME (SECONDS)
0
300
600
900
1200
1500
1800
Ag THICKNESS
Å
AT START
AT 5 HOURS
AT 25 HOURS
AT 60 HOURS

Fig. 42



The effect of film thickness on the frictional properties of thin films of indium deposited on tool steel. A minimum friction is obtained for a film approximately 10^{-4} to 10^{-5} cm. thick.

Fig. 43

DIAGRAMATIC ARRANGEMENT OF
EXPERIMENTAL EQUIPMENT

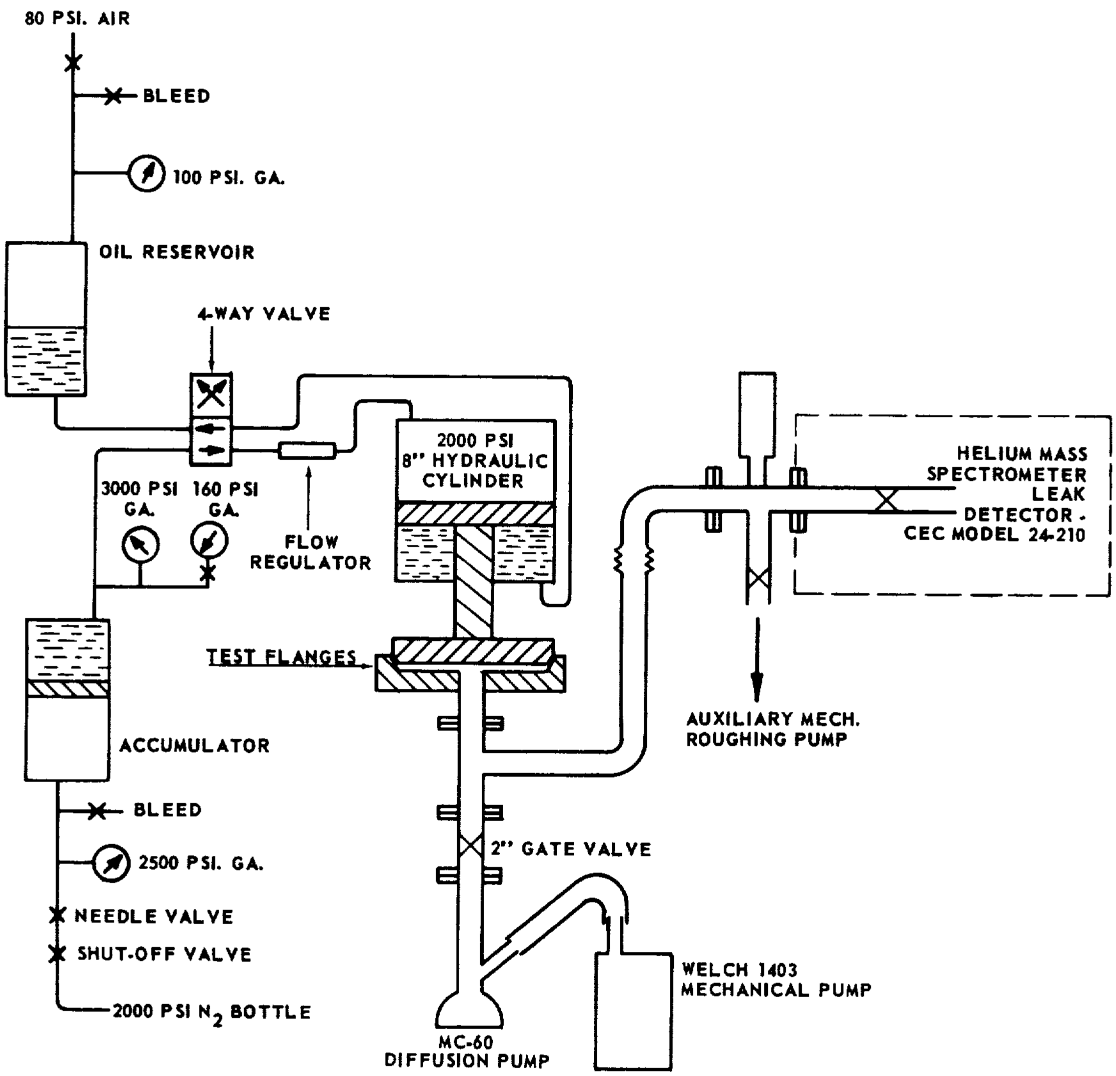


Fig. 44

APPROVAL MTP-P&VE-P-62-4

MECHANICAL ELEMENTS AND BEARINGS IN SPACE

by

Dr. W. R. Eulitz

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